ARPA-E Alternative Power Plant Cooling Workshop

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**Hotel Chicago
Chicago, IL**

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Presentation Topics

I   Framing the Problem

II Programmatic Objectives

III Transformative Technology Solutions

IV Proposed Performance Targets

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Framing the Problem

Water as a Global Problem

●More than 1.1 billion people across the globe currently lack access to safe drinking water

●Fresh water supplies are declining while populations are increasing

●United Nations predicts that by 2027 one third of the world will face water scarcity problems

●70% of global fresh water demand is used for agriculture

●It is estimated that 15-35% of irrigation practices worldwide are unsustainable due to pumping ground water aquifers faster than they can recharge

●International Food Policy Research Institute predicts 120% increase in food prices by 2025 due to fresh water shortages
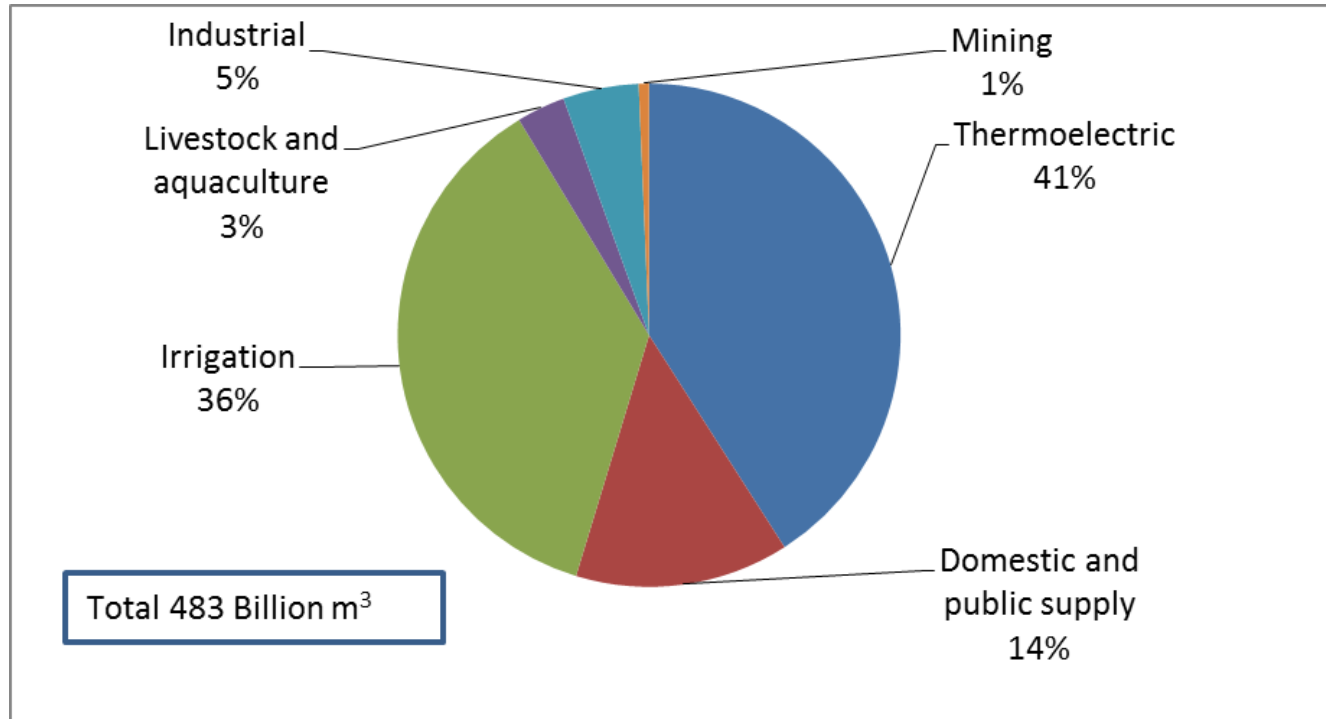

Complete Site Solutions
for Your Agricultural Needs

Energy/Water as a U.S. Problem

●41% of freshwater drawn in the U.S. is for thermoelectric power plant cooling

●3% of cooling tower water load is evaporated and dissipated

●Warming trend and over-pumping of natural water bodies places water cooling for thermoelectric power production at risk

●Desalination technologies in water stressed regions are energy intensive

●Water demand for fossil energy exploration and production is increasing

●Agricultural runoff water is damaging eco systems and is increasingly regulated

Majority of U.S. Fresh Water Withdrawal is for Cooling Thermoelectric Power Plants

Withdrawal (2005, US)

Pie chart:
- Industrial 5%
- Mining 1%
- Thermoelectric 41%
- Livestock and aquaculture 3%
- Irrigation 36%
- Domestic and public supply 14%
- Total 483 Billion m³

197 billion m³ annual withdrawal for thermoelectric power

*22 billion m³ withdrawn for cooling towers, **5 billion m³ dissipated***
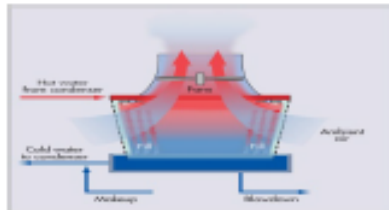*287 m³ water required per metric ton of potatoes produced*
***17.4 Mtons of potential food production dissipated** (more than 5 times world annual yield of potatoes)*

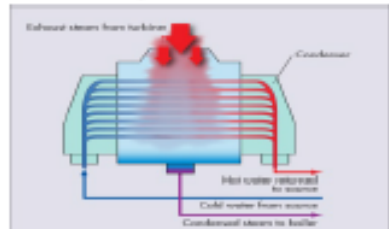# U.S. Power Plant Infrastructure is Heavily Reliant on Water Cooling

99% — **1%** — **<1%**

Water Cooling
- Cooling Tower[1] (42% in US)[2]
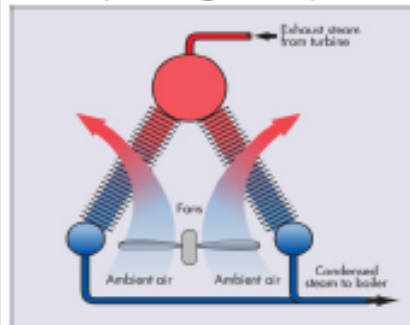- Once Through Cooling[1] (43% in US)[2]
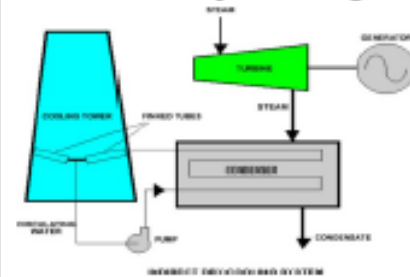- Cooling Pond (14% in US)[2]

Dry Cooling
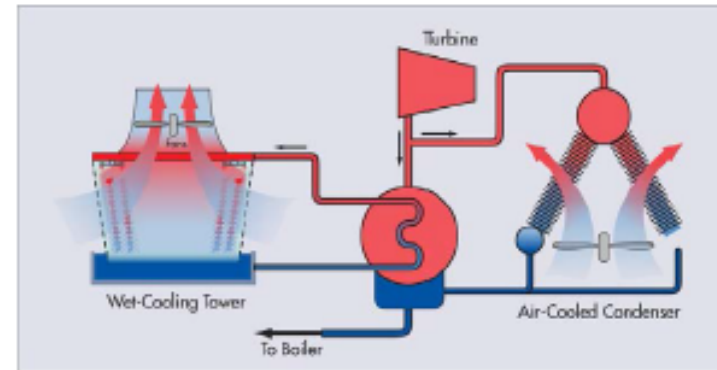- Direct Dry Cooling[1]: Air Cooled Condenser (1% Usage in US)[2]
- Indirect Dry Cooling[3]

Hybrid Cooling[1]

Increasing demand for dry cooling in water scarcity regions.

1. EPRI Report, "Water Use for Electric Power generation", No. 1014026, 2008.
2. Report of Department of Energy, National Energy Technology Laboratory, "Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements", DOE/NETL-400/2008/1339, 2008
3. http://www.globalccsinstitute.com/publications/evaluation-and-analysis-water-usage-power-plants-co2-capture/online/101181

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Current Trends in Consumption, Population Growth, and Climate, Create Barriers for Power Plant Water Cooling

- Lack of water availability/drought/population growth
  - Regional problems (FL, TX, CA)

- Rising water temperature and effluent temperature limits
  - Curtailed production for existing plants
  - Permitting restrictions for new plants
  - EPA 316a – thermal discharge limits

- Other Regulations
  - EPA 316b putting more difficult requirements on once-through cooling systems

Lack of Water Availability/Drought

U.S. Drought Monitor
West
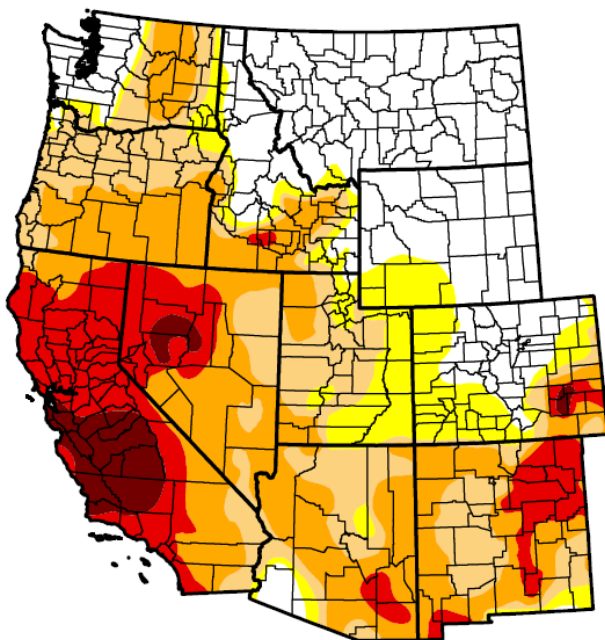
U.S. Drought Monitor
Texas
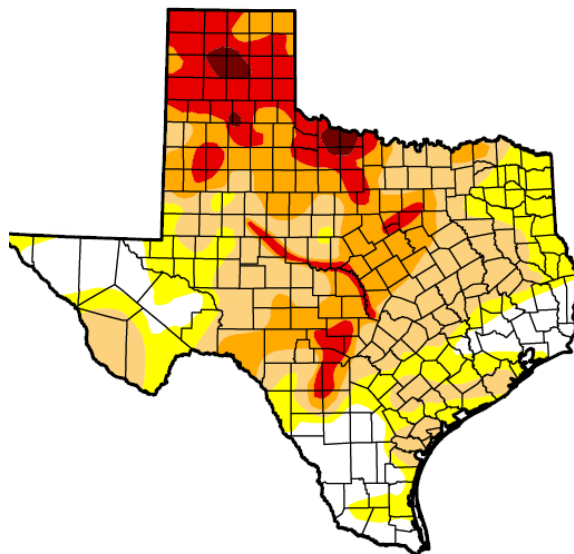
March 18, 2014
(Released Thursday, Mar. 20, 2014)
Valid 7 a.m. EDT

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	28.49	71.51	60.44	41.95	16.19	3.61
Last Week 3/11/2014	27.09	72.91	58.65	40.20	15.27	3.61
3 Months Ago 12/17/2013	22.53	77.47	51.20	30.61	7.56	0.63
Start of Calendar Year 12/31/2013	22.20	77.80	51.44	31.11	7.75	0.63
Start of Water Year 10/1/2013	25.25	74.75	58.96	34.18	5.57	0.63
One Year Ago 3/19/2013	22.56	77.44	63.05	41.15	15.72	3.13

Intensity:

D0 Abnormally Dry
D1 Moderate Drought
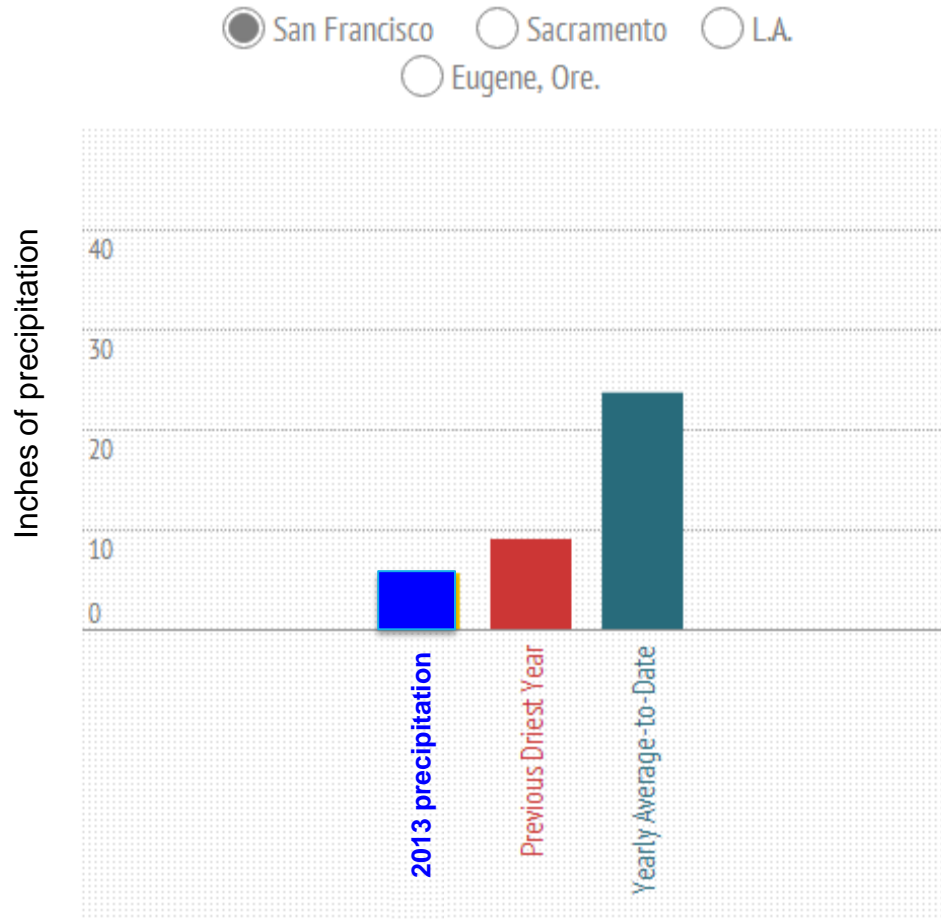D2 Severe Drought
D3 Extreme Drought
D4 Exceptional Drought

The Drought Monitor focuses on broad-scale conditions.
Local conditions may vary. See accompanying text summary
for forecast statements.

Author:
Eric Luebehusen
U.S. Department of Agriculture

http://droughtmonitor.unl.edu/

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Drought Vulnerability Impacts Regional Food Production

A Record Dry 2013

◉ San Francisco ○ Sacramento ○ L.A.
○ Eugene, Ore.

Inches of precipitation

- 2013 precipitation
- Previous Driest Year
- Yearly Average-to-Date

Almond Farm , February 25, 2014 in Turlock, California.

At ARPA-E: HOPE IS NOT A STRATEGY

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Current Challenges in Water Supply Impacting Regional Power Production

Figure 1. Selected events over the last decade illustrate the U.S. energy sector's vulnerabilities to climatic conditions

Current Challenges in Regional Water Supply Impacting Power Production

Aug '12: Water temperatures were the warmest since operations began in 1970. Temperature of the intake cooling water was too high and exceeded technical specifications of the reactor. A nuclear reactor was shut down. loss of 255,000 megawatt-hours of power, worth several million dollars in lost production
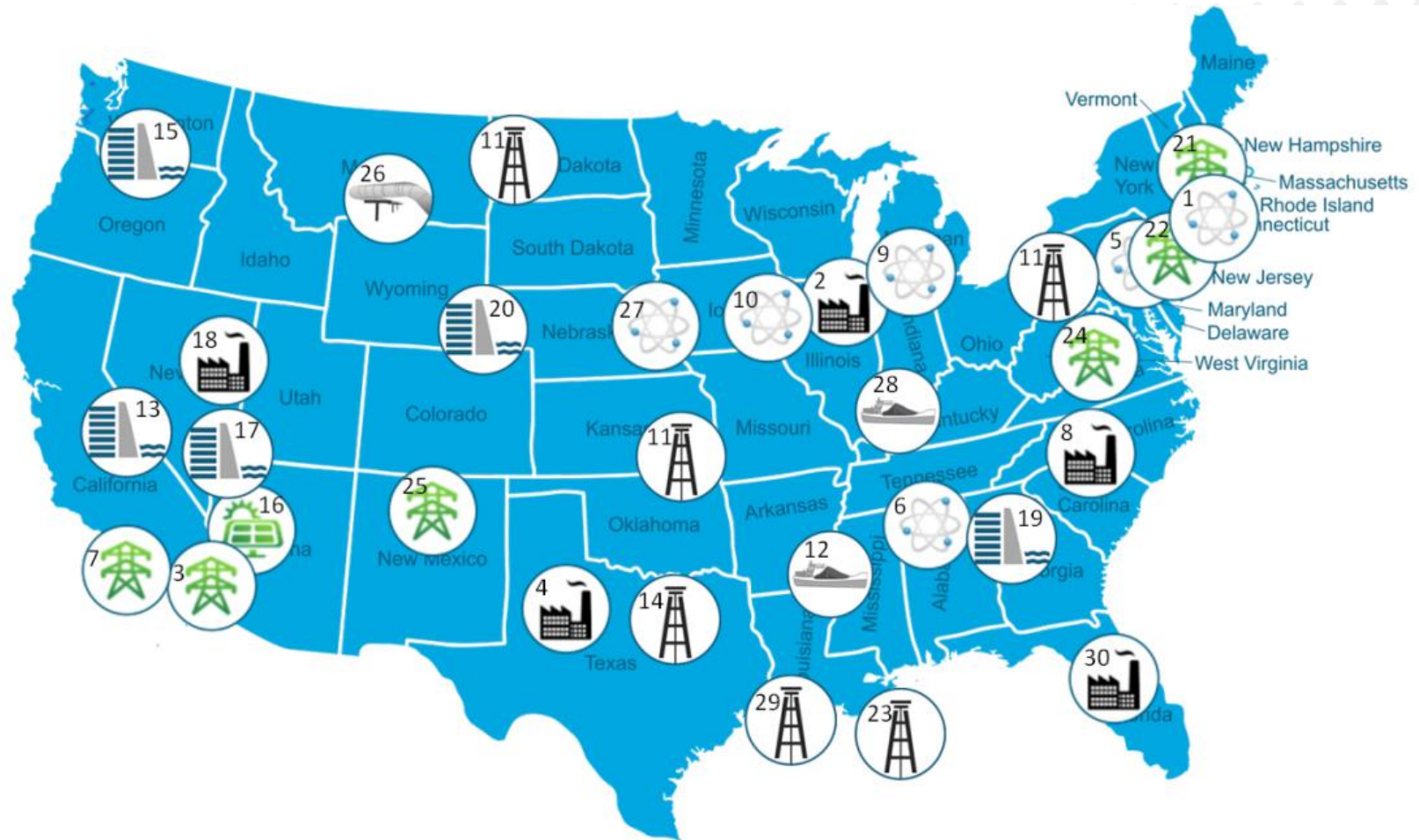
Figure 1. Selected events over the last decade illustrate the U.S. energy sector's vulnerabilities to climatic conditions

Current Challenges in Regional Water Supply Impacting Power Production

July 2012: Four coal-fired power plants and four nuclear power plants requested permission to exceed their permitted water temperature discharge levels
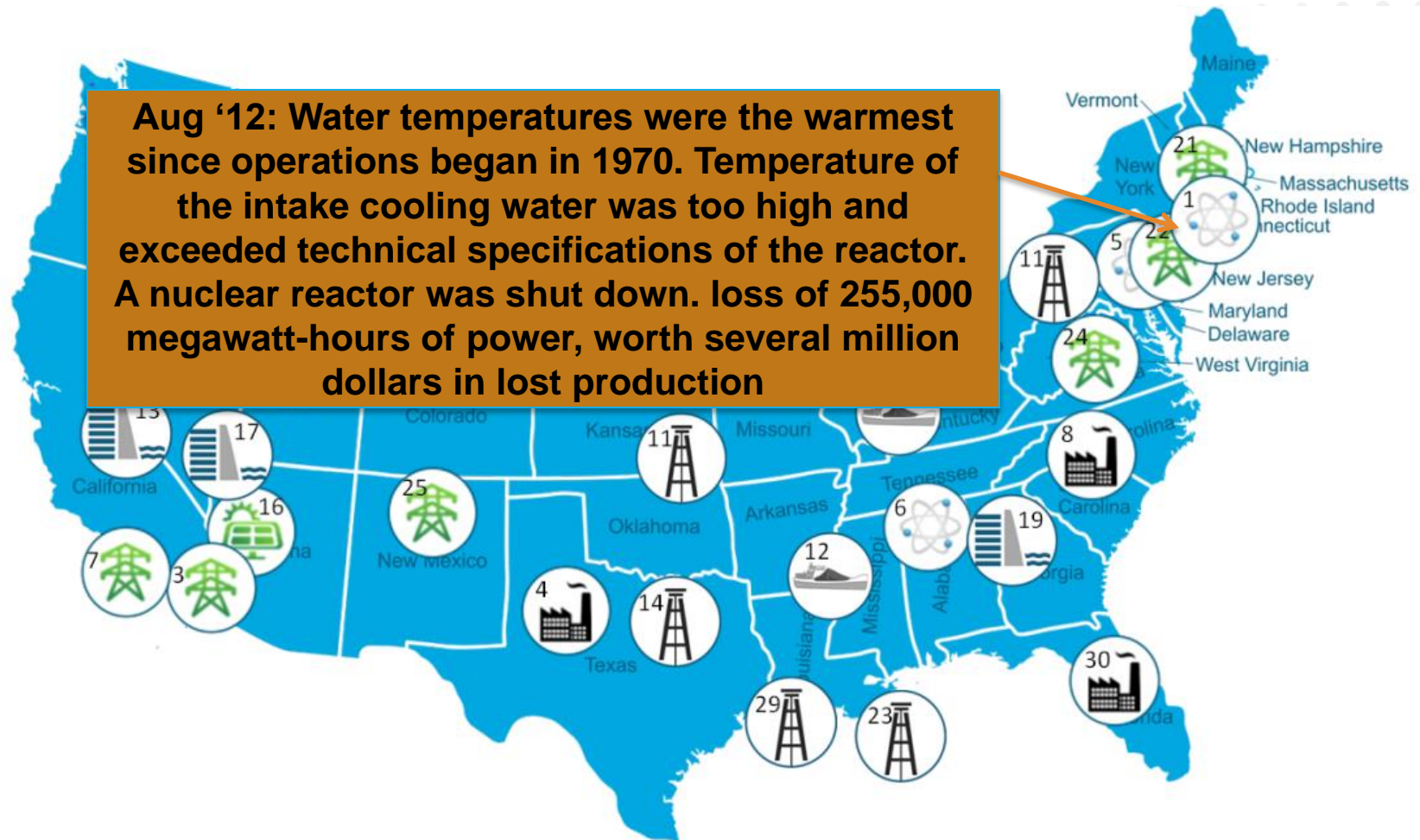
Figure 1. Selected events over the last decade illustrate the U.S. energy sector's vulnerabilities to climatic conditions

Current Challenges in Regional Water Supply Impacting Power Production

Summer 2011: Consecutive days of triple-digit heat and record drought resulted in one power plant reducing its output
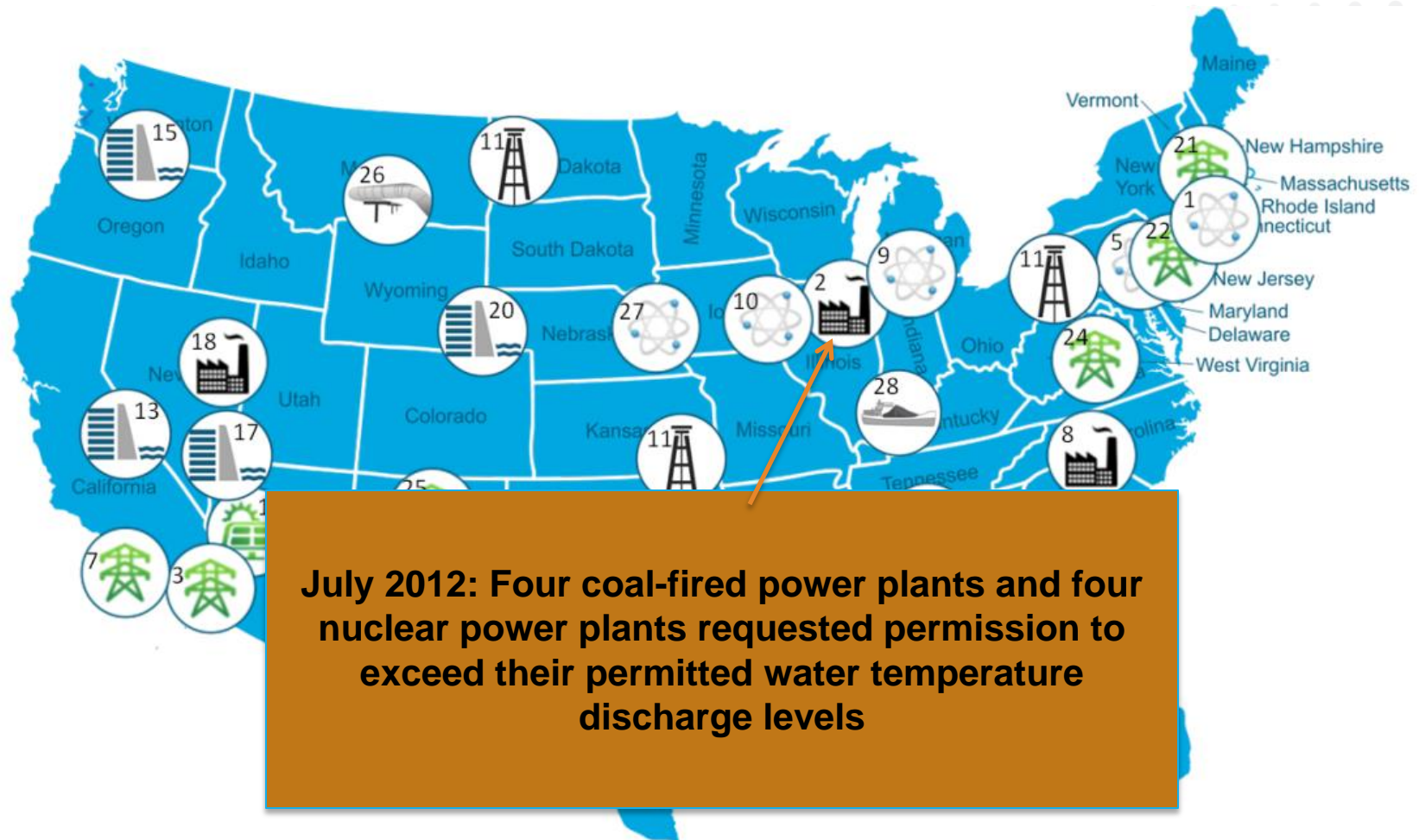
Figure 1. Selected events over the last decade illustrate the U.S. energy sector's vulnerabilities to climatic conditions

Current Challenges in Regional Water Supply Impacting Regional Power Production

Summer 2010: Two generating stations had to reduce power because the temperatures of the intake cooling water were too high and did not provide sufficient cooling for full power operations
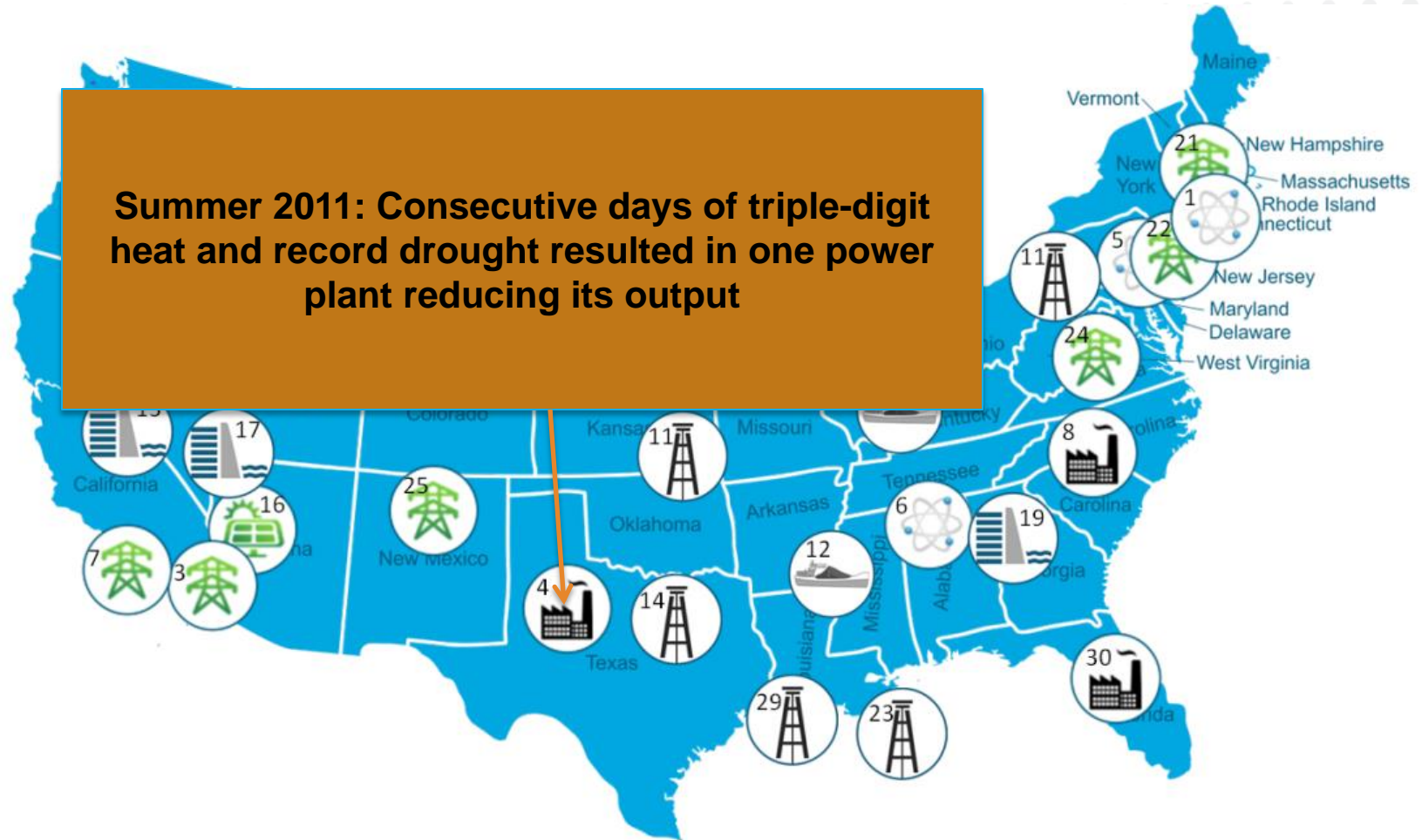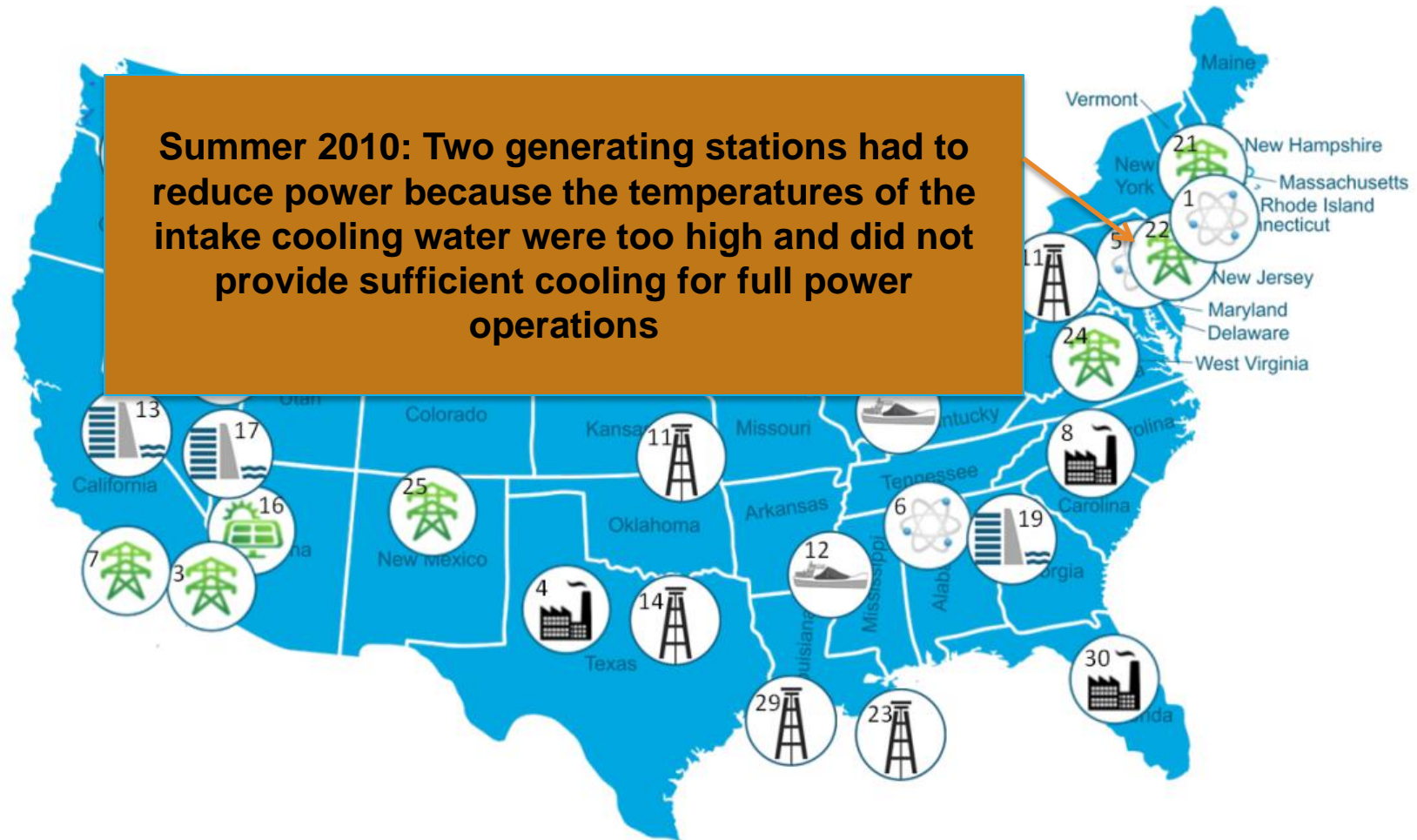
Figure 1. Selected events over the last decade illustrate the U.S. energy sector's vulnerabilities to climatic conditions

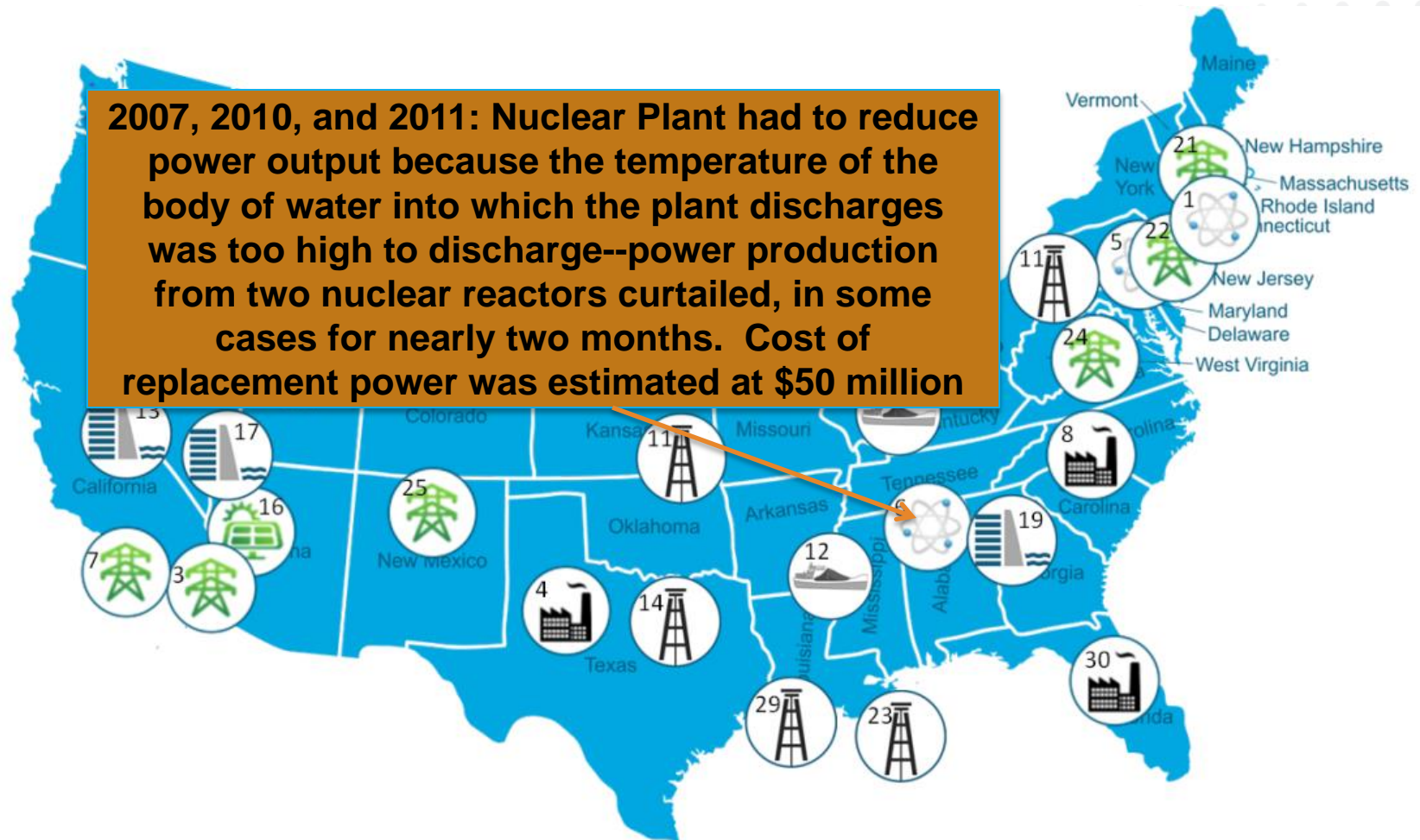# Current Challenges in Regional Water Supply Impacting Power Production

2007, 2010, and 2011: Nuclear Plant had to reduce power output because the temperature of the body of water into which the plant discharges was too high to discharge--power production from two nuclear reactors curtailed, in some cases for nearly two months. Cost of replacement power was estimated at $50 million
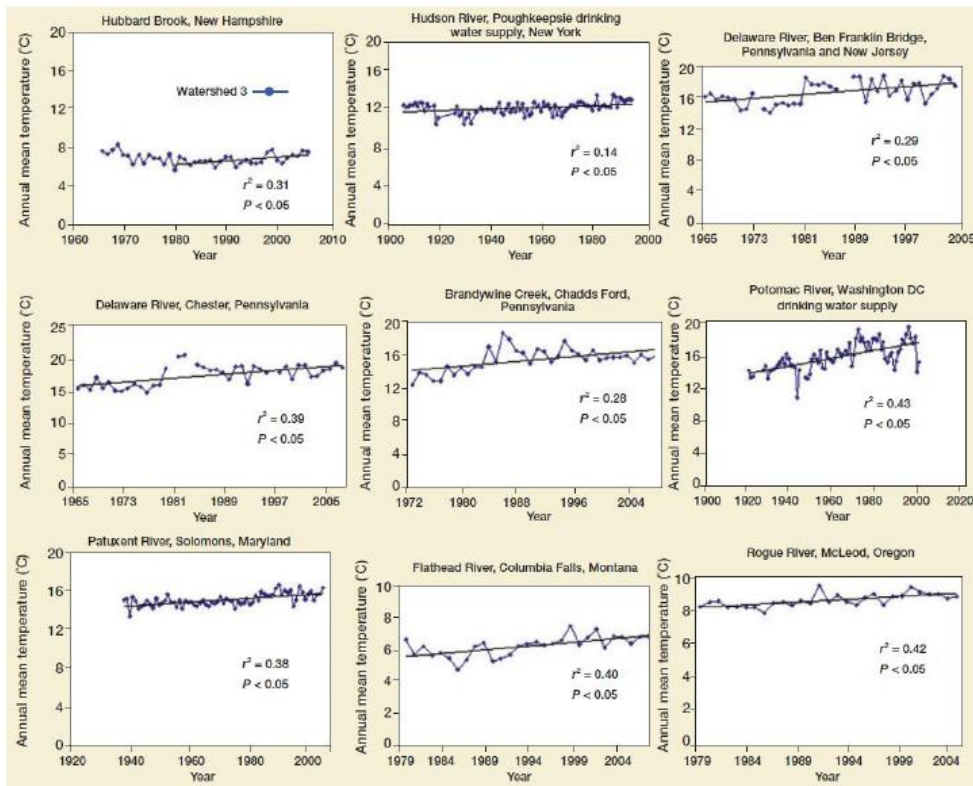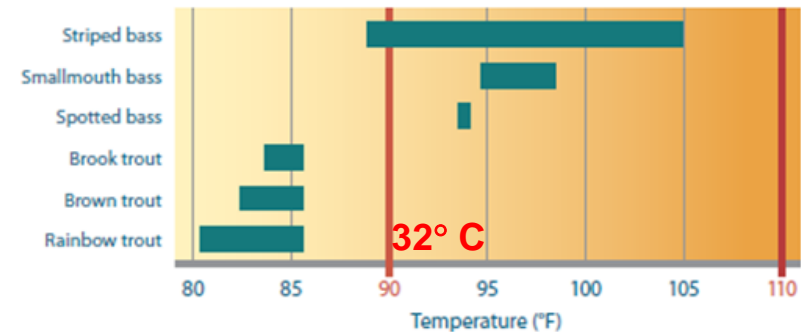
Figure 1. Selected events over the last decade illustrate the U.S. energy sector's vulnerabilities to climatic conditions

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Watershed Temperatures Reveal an Increasing Trend over a 100 Year Time Frame.
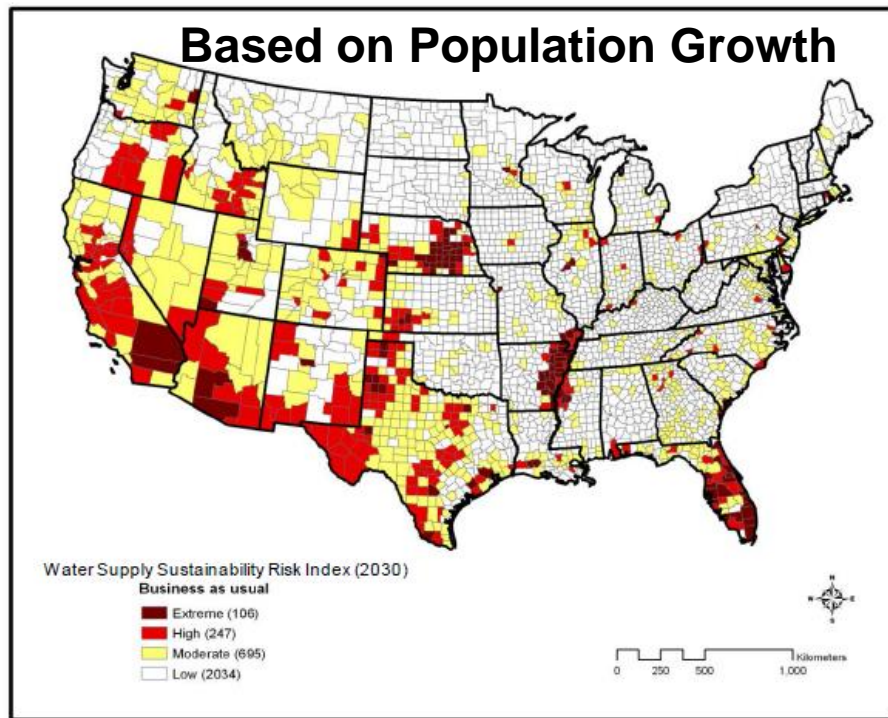

Source: Kaushal et al. 2010

Based on EPRI Study, ARPA-E Concludes Lack of Water Availability by 2030 Puts ~3 Quads at Risk

Based on Population Growth

Water Supply Sustainability Risk Index (2030)
Business as usual
- Extreme (106)
- High (247)
- Moderate (695)
- Low (2034)

Figure 5-9
Water supply sustainability risk index.

3.29 of 13.5Q electricity generation at risk

Power generation (Q) vulnerability in 2030

- ■ High/Extreme risk
- ■ Already Dry Cooled
- ■ Other Undocumented or Uncooled
- ■ No/Low risk
- ■ No Cooling Required
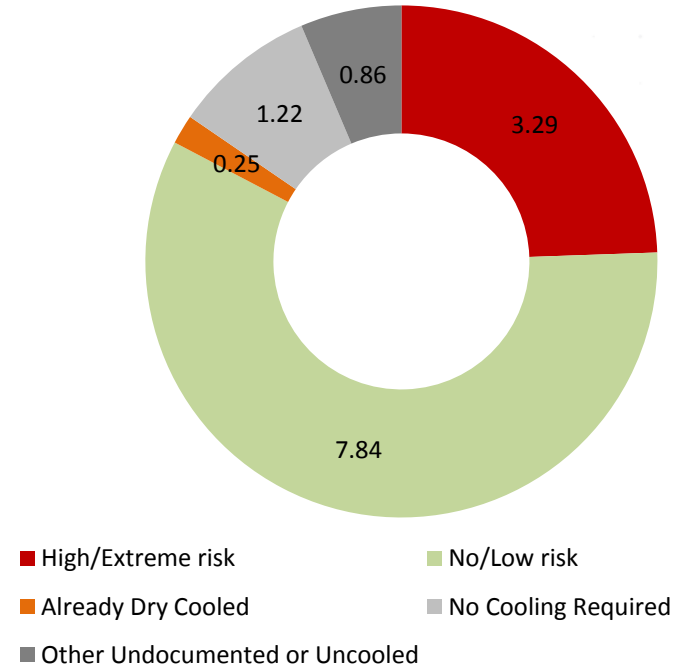
Notes/Assumptions
- Analysis does not yet consider *projected* plants – this is only existing production
- BAU means water supply/supply trends at 2005 levels, but population growth ~1%/yr (US Census Bureau)
- Water use/requirements *per capita* remain at 2005 levels
- No climate change is considered

New EPA Regulations Impose Barriers to Water Cooling for Future Power Production

● Rule 316(b) of the Clean Water Act requires "best technology available" to minimize the mortality of aquatic life associated with power plant cooling.

● Approximately 2.1 billion marine lives killed per year due to power plant intake on once through cooling systems

● EPA Rule 316(b) Phase II requires 80-95% reduction in impingement mortality; will all but phase out once through cooling (>40% of U.S. installations—550 facilities) as a viable option

● EPA Rule 316(a) limits water temperature discharge back to water source ($T_{discharge}$<32 °C)

Dead fish cause nuke plant shutdown
A massive die-off of moon jellyfish clogged the cooling water intake filters at FPL's St. Lucie nuclear power plant in St. Lucie in late August. The event led to a temporary shutdown of the plant and killed dozens of protected Goliath Groupers and other fish, filling the entire intake canal with carcasses that had to be hoisted out by crane.

Intake filters clogged with jellyfish

Reactor 2

Reactor 3

St. Lucie COUNTY

Fort Pierce

Area of detail

Port St. Lucie

St. Lucie nuclear power plant

Tentacles from dead jellyfish kill about 5 tons of protected goliath grouper, other fish.

Huge pipes offshore that bring in cooling water pull in huge numbers of jellyfish.

Sources: Google Images; St. Lucie Nuclear Power Plant
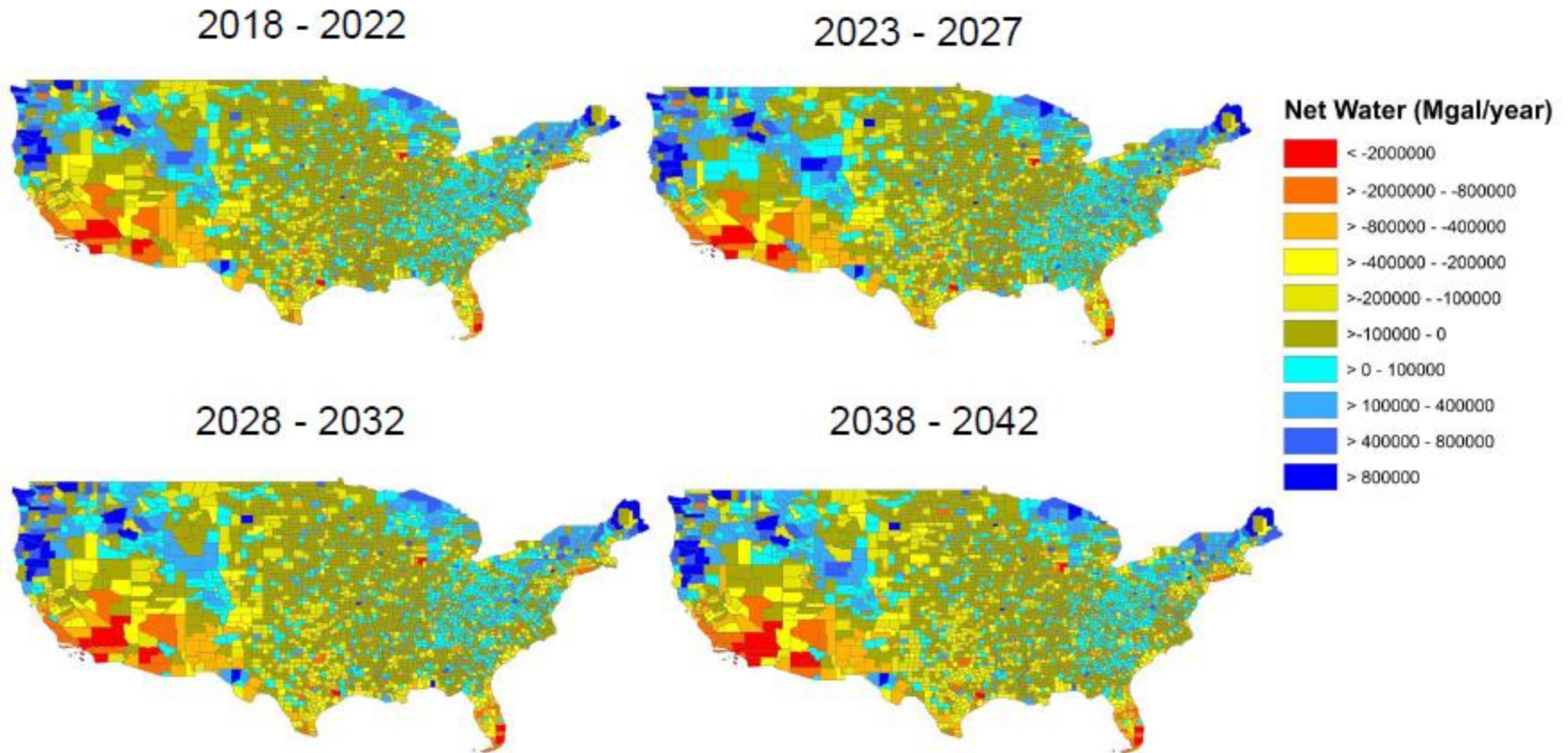
CHRISTOPHER SMITH/Staff Artist

Peering Into the Future

●**2012 Northeastern University study, which considers population growth and climate changes, predicts water shortages on a national scale by 2050**

●**ARPA-E Commissions Northeastern University to study effects of population growth and climate change on water availability and water temperature in 4 yr increments out to 2042**

Water Supply Sustainability Index (2050)

- Extreme (412)
- High (608)
- Moderate (1192)
- Low (897)
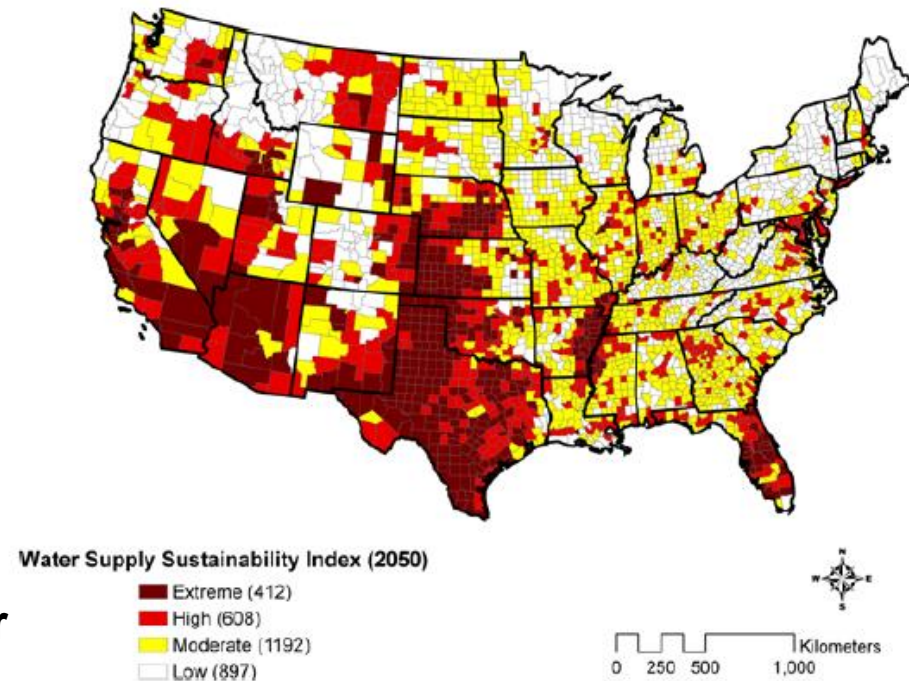
Northeastern Study Suggests that Negative Water Scenarios Grow Into A National Problem

2018 - 2022

2023 - 2027

2028 - 2032

2038 - 2042

Net Water (Mgal/year)

■	< -2000000
■	> -2000000 - -800000
■	> -800000 - -400000
■	> -400000 - -200000
■	>-200000 - -100000
■	>-100000 - 0
■	> 0 - 100000
■	> 100000 - 400000
■	> 400000 - 800000
■	> 800000

Continued Reliance on Water Cooling for Thermoelectric Power Plants is Risky

●Negative water recharge expected to grow significantly over next 15 years

●More stringent EPA regulations on water intake and thermal discharge will render once-through cooling obsolete

●Rising water temperatures adversely impact power production and efficiency (**3° C rise in condenser temperature results in 1% reduction in power production**)

Current Trends in Greenfield Power Plant Cooling—Air Cooled Condensers

ACC installation in California

- Air-Cooled Condensers (ACCs)
  - Obtaining a water permit is too costly with uncertain timeline
  - ACCs used as far North as Canada & Alaska; <60 Total ACCs units in US
- Lower Power Conversion Efficiency
  - ACCs result in 1-5 % loss of power output from turbine
  - CO_2 emissions/kW-h increase
- Maintenance
  - Issues with wind loading, fan failure, fan noise, corrosion, & leakage persist

Programmatic Objectives

Alternative Power Plant Cooling Program Objectives

Develop transformative power plant cooling technologies that enable:

I.   Zero water dissipation to the atmosphere
II. No loss of power production efficiency
III. Compliance with EPA Rule 316(b) Phase II

Transformative Technology Solutions

Importance of Sink Temperature to Steam Power Production

Lower sink temperature allows more work to be extracted from turbine, which yields higher cycle efficiency

Turbine back pressure is defined by the sink temperature
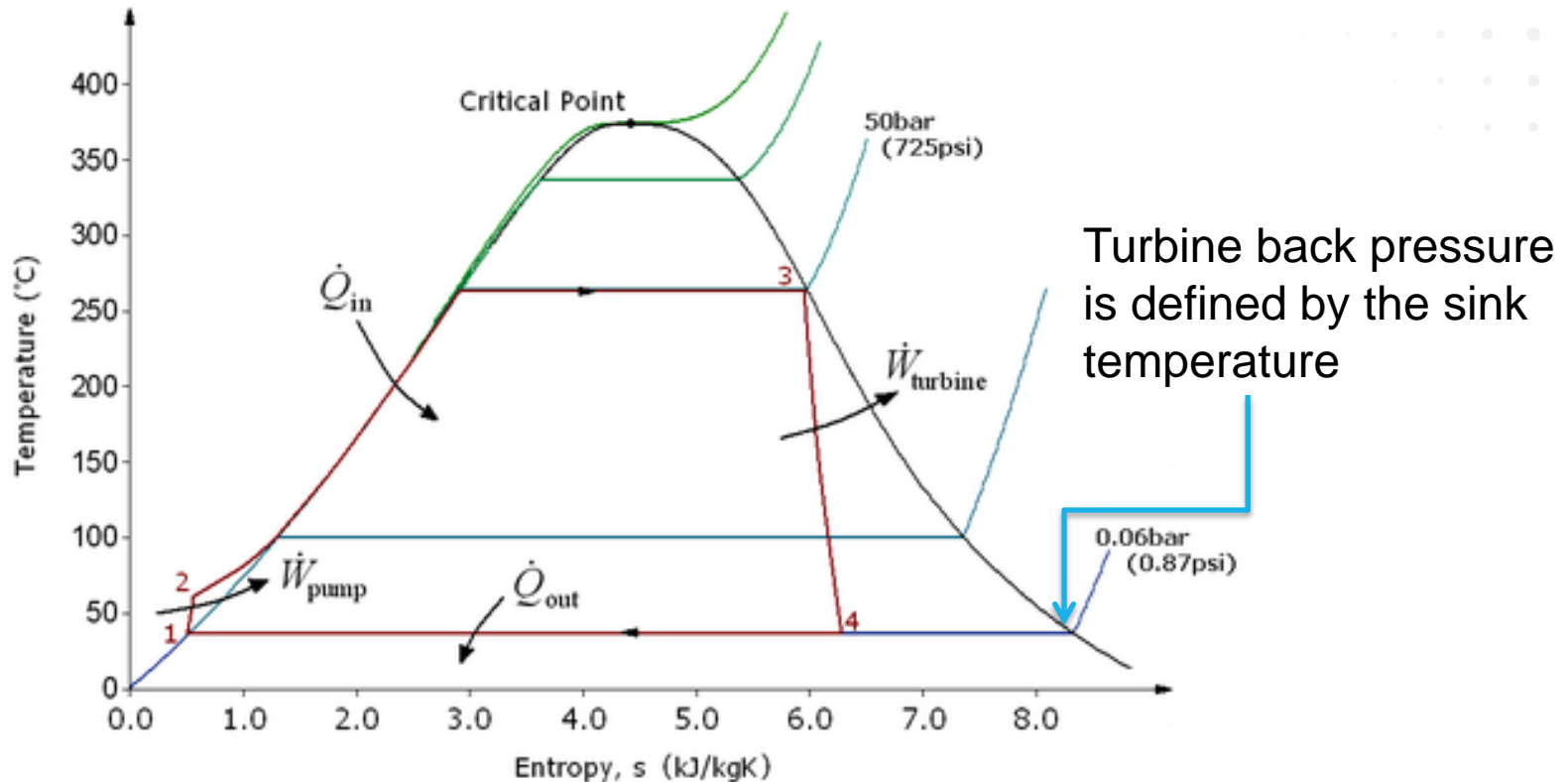
Why Not Cool With Air?

- **Challenge 1: higher capital cost since more HX area required**

$$q = UA\Delta T_{LM}$$

$$\frac{1}{UA} = \sum \frac{1}{hA} + \sum R$$

For forced air, h ≈ 10 – 100 W/m²K
For water, h ≈ 500 – 10,000 W/m²K

- Convection heat transfer coefficient for water is several orders of magnitude higher than air.
- Significantly more heat transfer area required for air cooled HX

- **Challenge 2: temperature of air is variable and often above the design point**

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Lost Power Production due to Backpressure Above the Turbine Design Point (El Paso, TX)

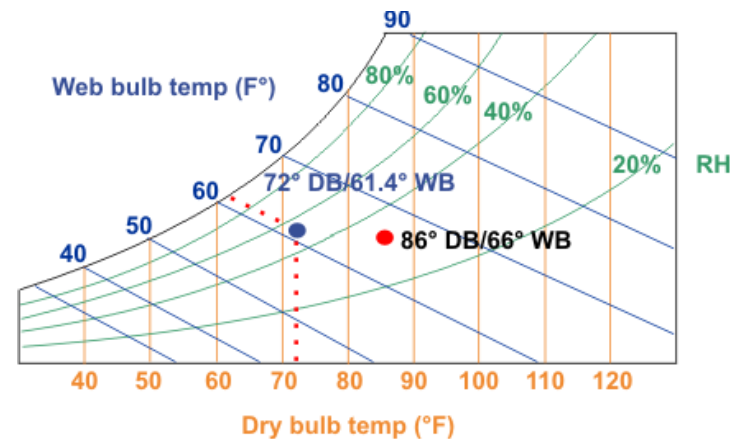**EPRI study comparing Air Cooled Condenser vs Cooling Tower Retrofit**
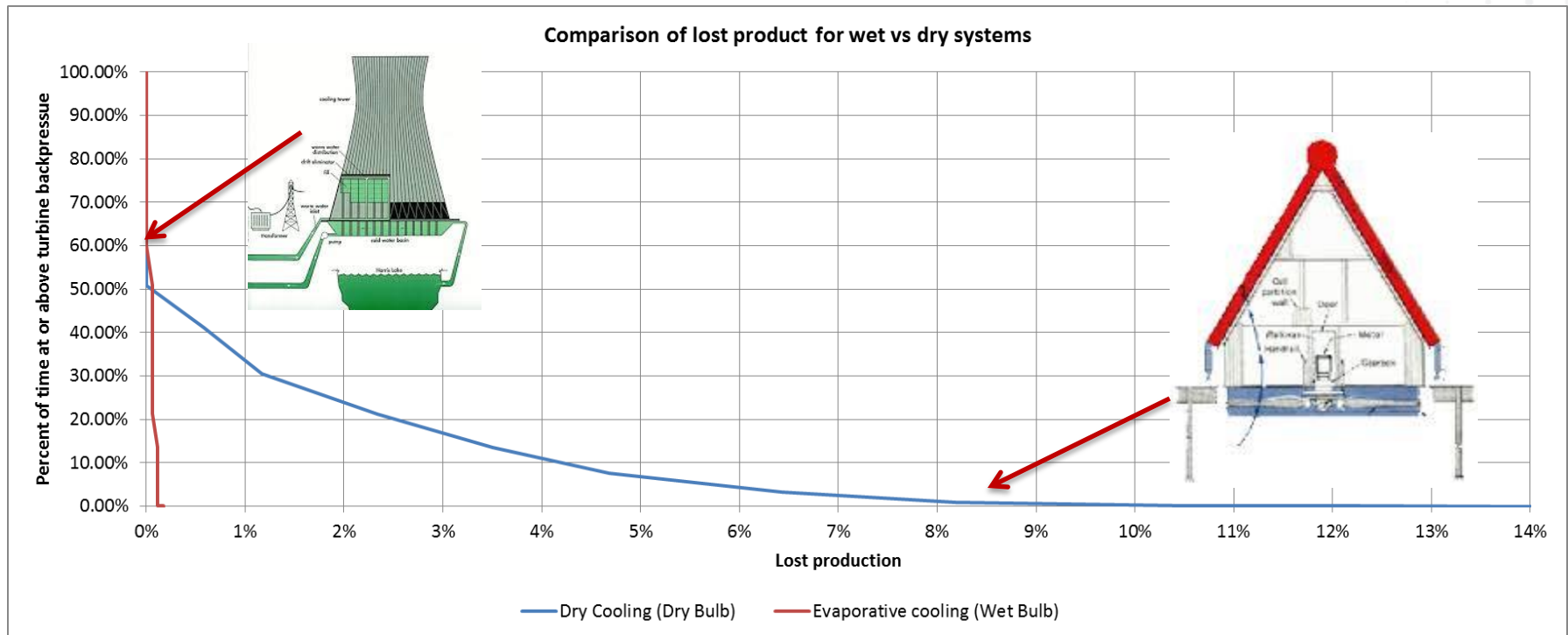
What is Wet Bulb Temperature? What is Attractive About Cooling Towers?
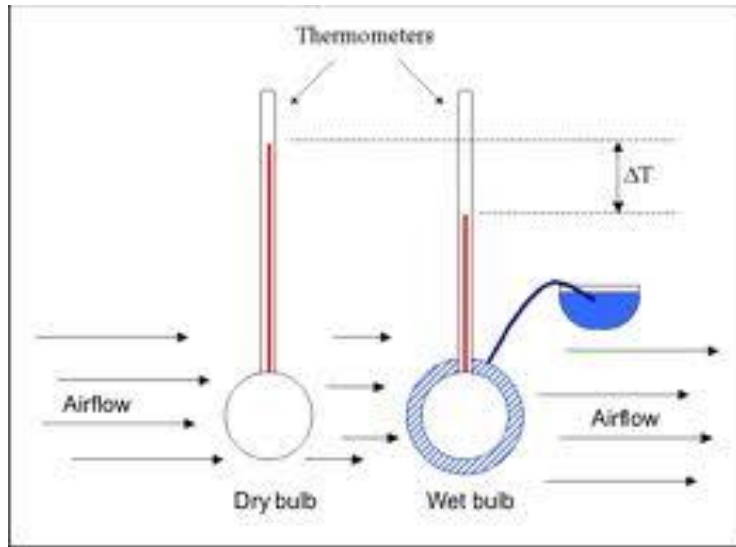
- Wet bulb temperature is the water temperature that can be achieved by evaporating into and fully saturating surrounding ambient air

- Cooling towers provide an inexpensive means for cooling water below ambient air temperature

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Design 1%
Boston	Wet Bulb	27.5	29.3	36.3	44.6	53.9	62.7	67.9	67.4	61.5	52.0	42.6	32.6	74.0
	Dry Bulb	33.0	35.3	43.2	53.5	63.8	73.9	80.0	78.2	70.4	59.9	49.5	38.4	88.0
Jacksonville	Wet Bulb	52.9	55.3	59.6	64.5	70.3	75.1	77.1	77.1	75.1	69.1	63.1	55.9	79.0
	Dry Bulb	59.8	63.6	70.3	76.6	83.0	87.2	89.3	88.1	85.1	77.8	70.6	62.6	93.0
Chicago	Wet Bulb	23.3	27.0	37.2	46.6	56.6	64.9	69.8	69.3	62.2	51.2	39.1	27.9	76.0
	Dry Bulb	27.6	31.8	43.9	55.7	67.9	77.4	82.5	80.6	72.4	59.9	45.0	32.2	89.0
Seattle	Wet Bulb	39.4	41.8	44.2	47.2	52.0	56.0	59.2	59.6	57.2	51.0	44.0	39.7	65.0
	Dry Bulb	44.3	47.8	51.5	55.6	61.8	67.2	71.6	71.6	67.3	58.1	49.0	44.3	82.0

Table 3-13: Time-Weighted Averages for Eight-Hour Period from 8am to 4pm (°F)
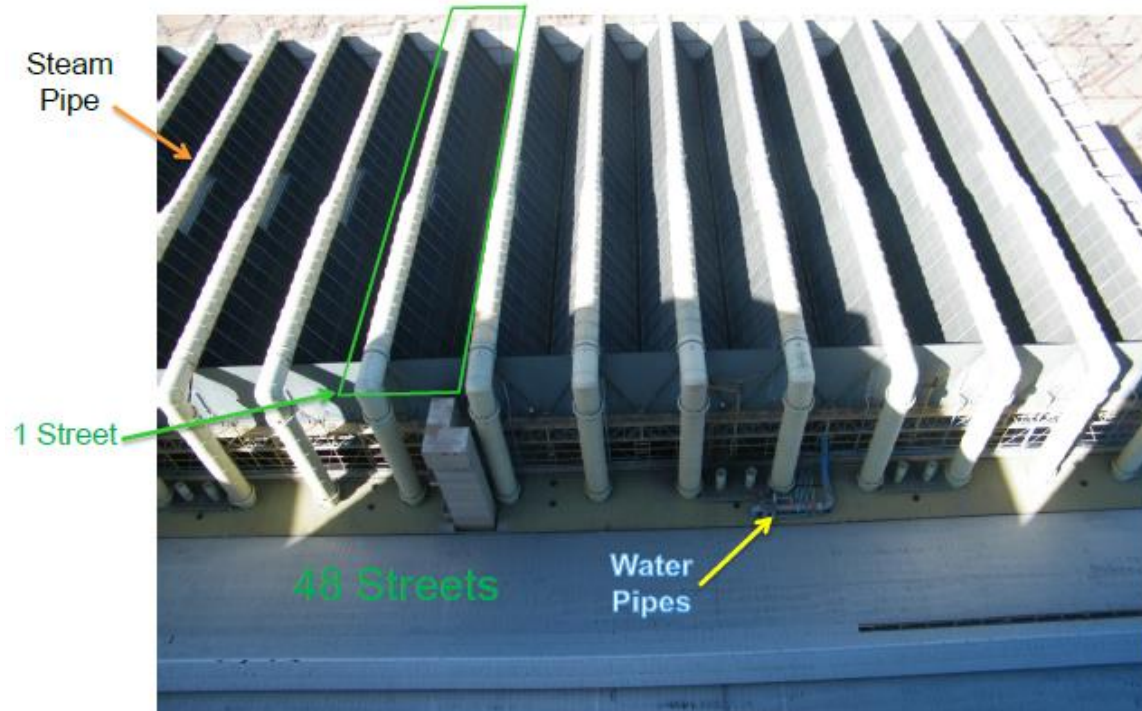
Air Cooled Condensers are Used on a Limited Basis

Air is poor heat transfer fluid: large surface areas required (condenser tubes: 10-11 external fins per inch, with a tube length of ~7+ miles of tube per MW of generator output)

Drawbacks with Air Cooled Condensers

Courtesy of Jessica Shi; EPRI

- High cost (up to 5 times greater than wet cooling tower systems) due to large size and poor heat transfer

- Approximately 9% increase in LCOE

- Lower power conversion efficiency

- Finned surfaces susceptible to freezing during winter

- A-Frames are susceptible to high wind loading

- Higher maintenance costs

Higher Costs Associated with Air Cooled Condensers

Comparison of annualized costs for wet and dry cooled power plant systems in various climates
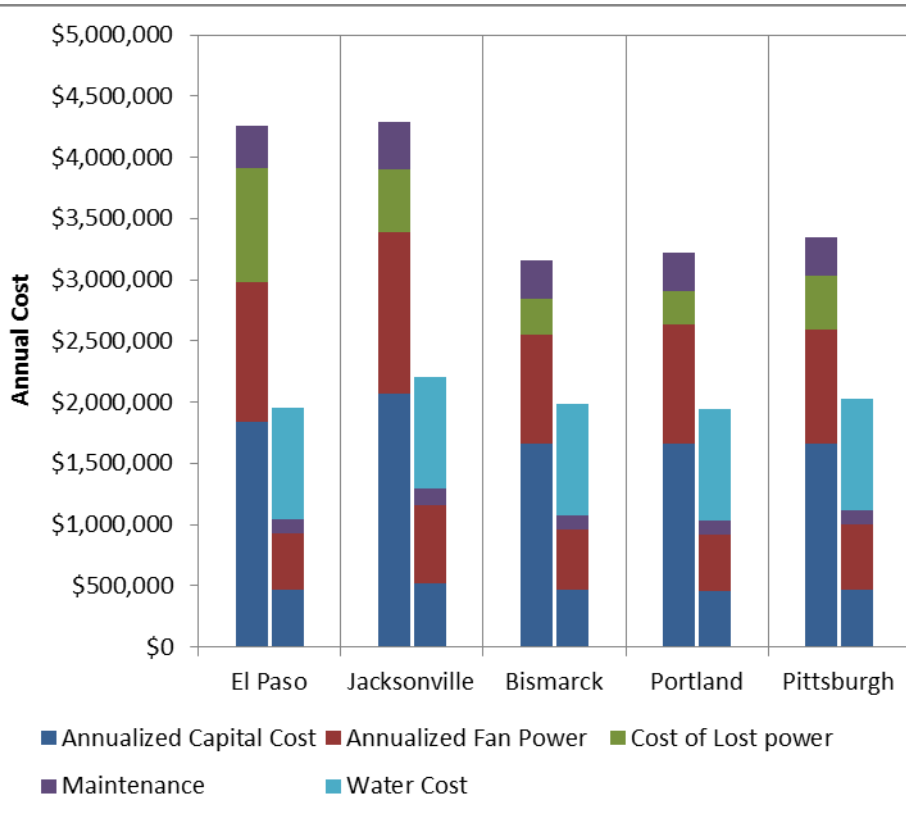
Lower heat transfer coefficient:
- more HX area required
  - Higher annualized capital cost
  - Higher maintenance cost
- Heat transfer coefficient can be increased by higher velocities; more fan power required

Using dry bulb temperature in lieu of wet bulb temperature
- Decreased performance results in lost power cost

8-10% increase in LCOE with ACC

http://www.nrel.gov/docs/fy06osti/40163.pdf
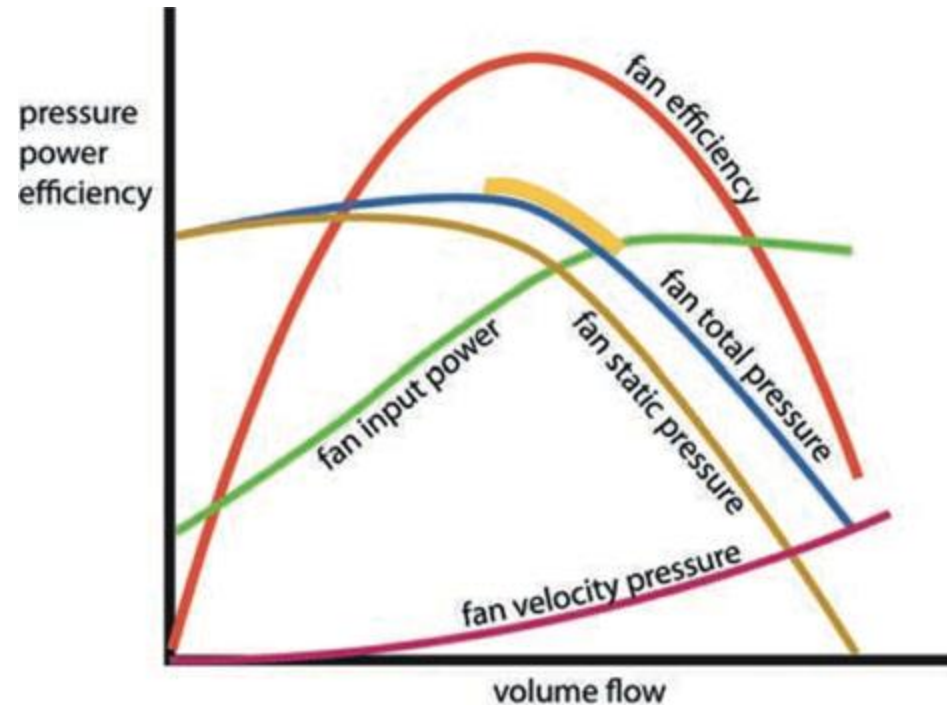
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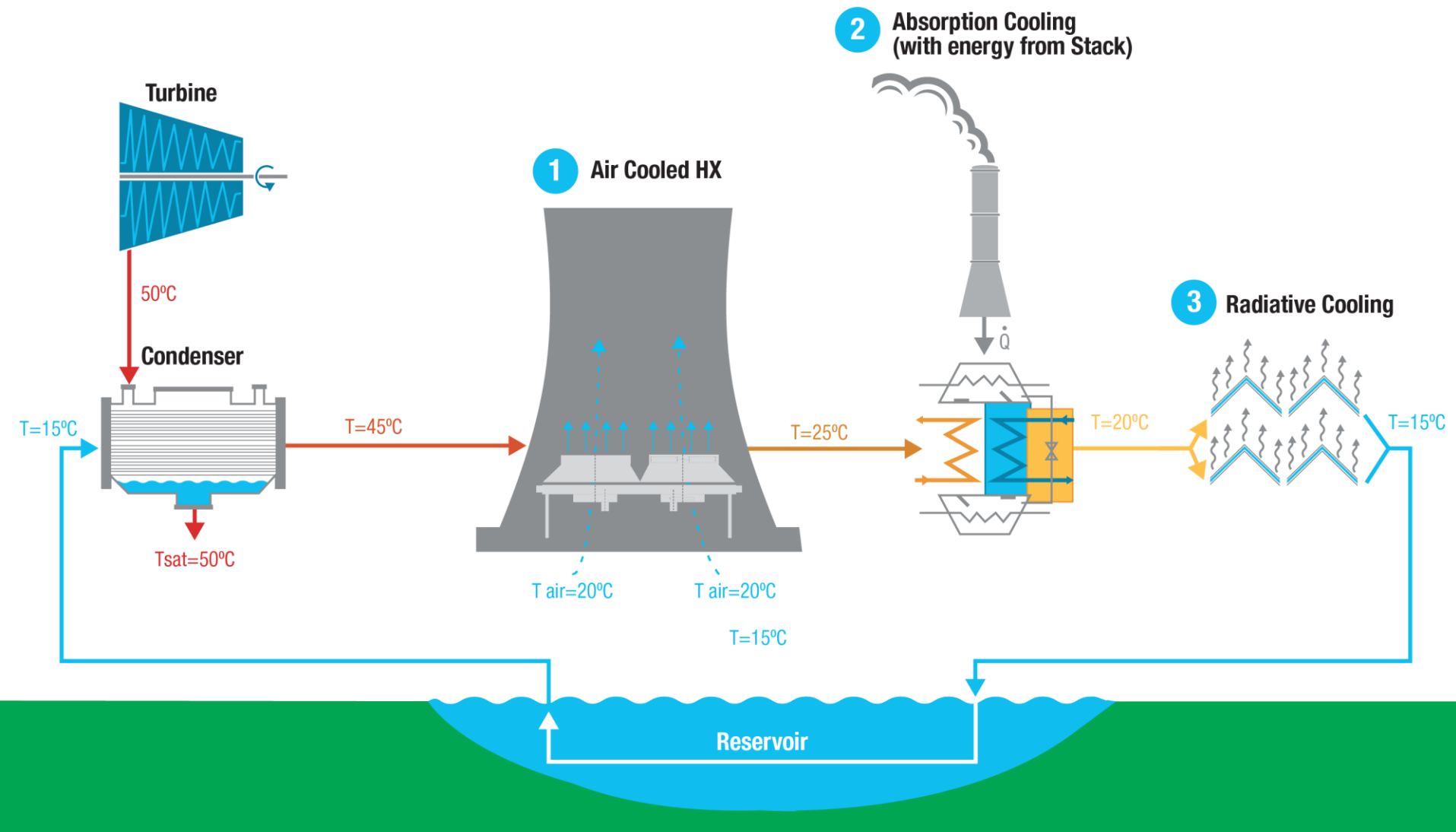
Air Pumping Imposes a Parasitic Load

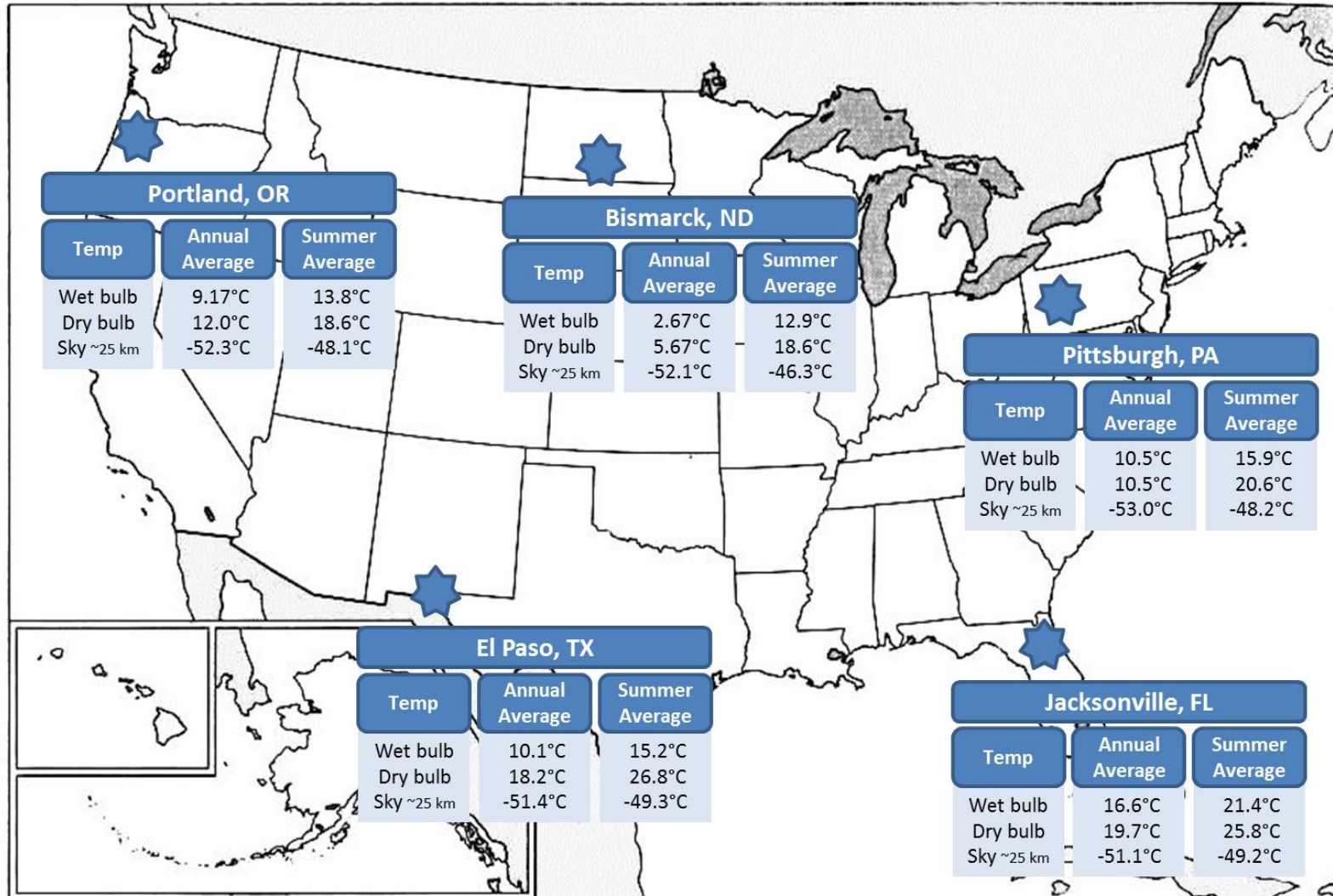**Fan efficiency falls off significantly away from the design point**

Courtesy of Jessica Shi; EPRI

Indirect Dry Cooling in Stages: Air, Absorption, & Radiative Cooling Meets Programmatic Objectives

Different Climates May Require Different Solutions

Portland, OR

Temp	Annual Average	Summer Average
Wet bulb	9.17°C	13.8°C
Dry bulb	12.0°C	18.6°C
Sky ~25 km	-52.3°C	-48.1°C

Bismarck, ND

Temp	Annual Average	Summer Average
Wet bulb	2.67°C	12.9°C
Dry bulb	5.67°C	18.6°C
Sky ~25 km	-52.1°C	-46.3°C

Pittsburgh, PA

Temp	Annual Average	Summer Average
Wet bulb	10.5°C	15.9°C
Dry bulb	10.5°C	20.6°C
Sky ~25 km	-53.0°C	-48.2°C

El Paso, TX

Temp	Annual Average	Summer Average
Wet bulb	10.1°C	15.2°C
Dry bulb	18.2°C	26.8°C
Sky ~25 km	-51.4°C	-49.3°C

Jacksonville, FL

Temp	Annual Average	Summer Average
Wet bulb	16.6°C	21.4°C
Dry bulb	19.7°C	25.8°C
Sky ~25 km	-51.1°C	-49.2°C

Sources: *EPRI Comparison of Alternate Cooling Technologies for US Power Plants; NOAA Satellite and Information Service*
Data averaged from 1973-1996
Sky temperatures taken at 20 mb

Transformational Air Cooled HX Concepts

- Low cost air cooling strategies that significantly increase air side heat transfer coefficient without increasing pressure drop
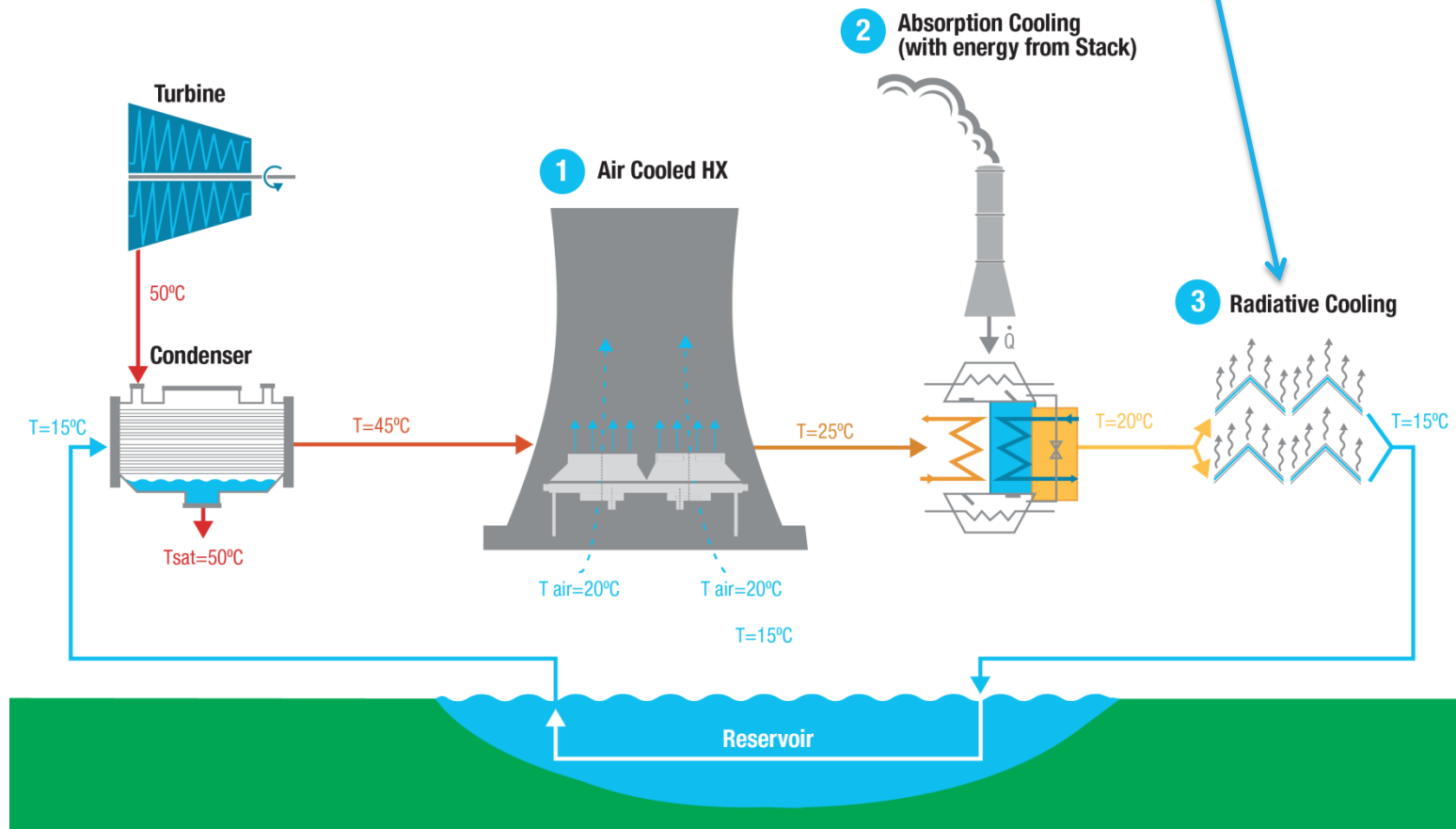- Efficient forced draft technologies coupled to natural draft
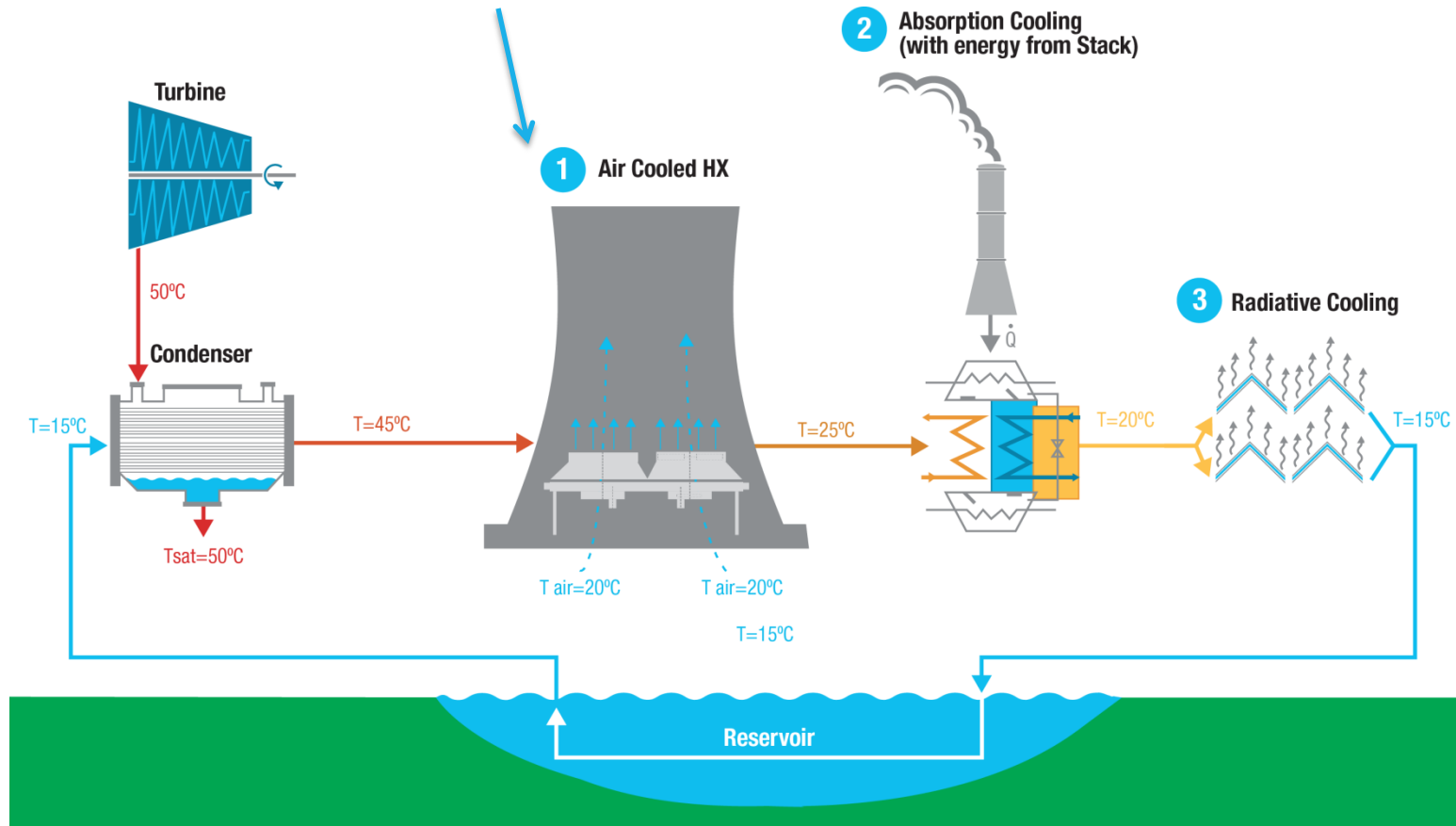
Transformational Absorption Cooling Concepts

Waste heat capture from the stack and absorption cooling systems with high COP
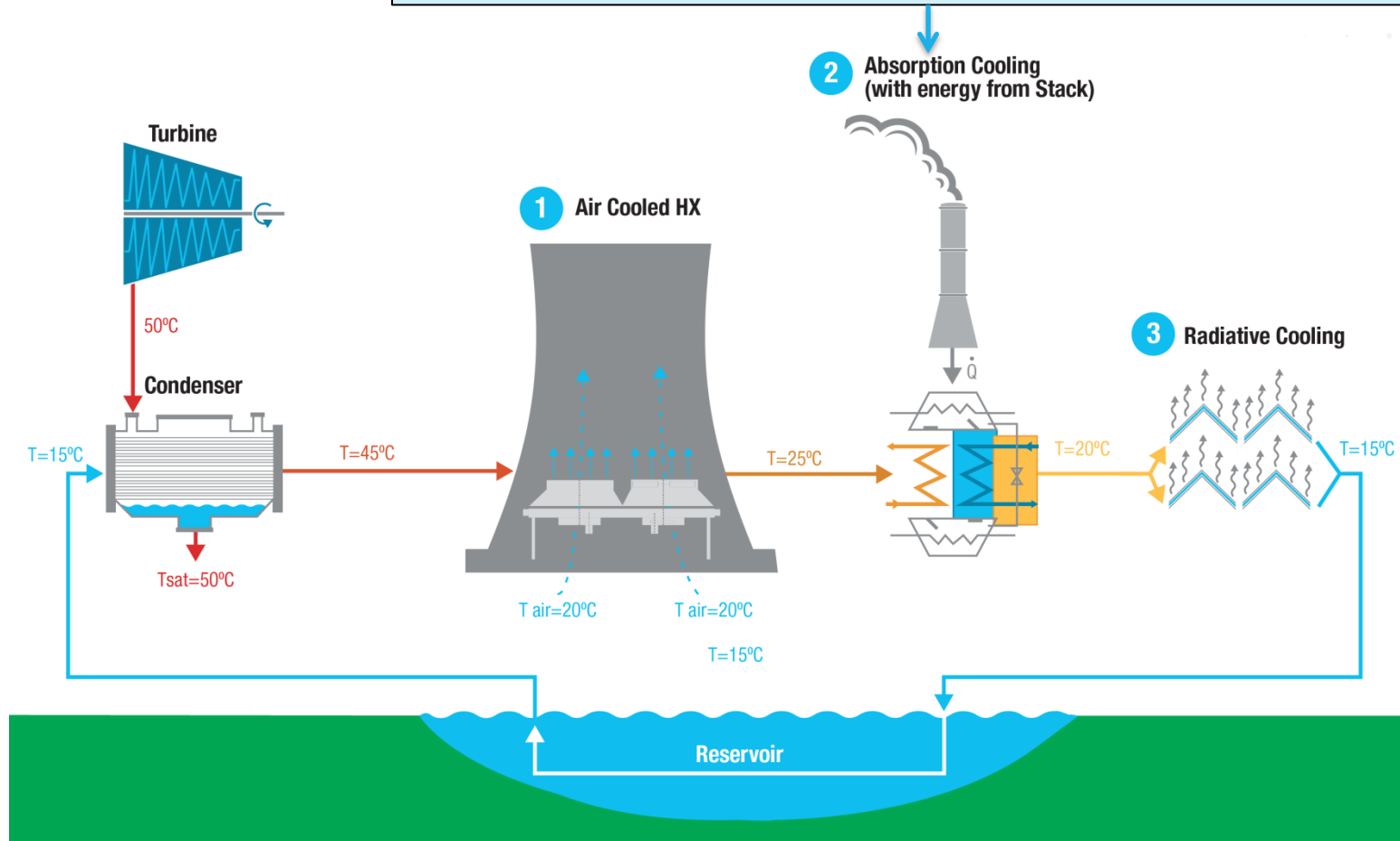
Transformational Radiative Cooling Concepts

High performance radiant cooling coatings and associated technologies

2 **Absorption Cooling** (with energy from Stack)

Turbine

1 **Air Cooled HX**

3 **Radiative Cooling**

50ºC

Condenser

T=15ºC

T=45ºC

T=25ºC

T=20ºC

T=15ºC

Tsat=50ºC

T air=20ºC   T air=20ºC

T=15ºC

Reservoir

Advanced manufacturing to enable low cost

Advanced manufacturing technologies to fabricate transformational designs at the MW scale with low cost
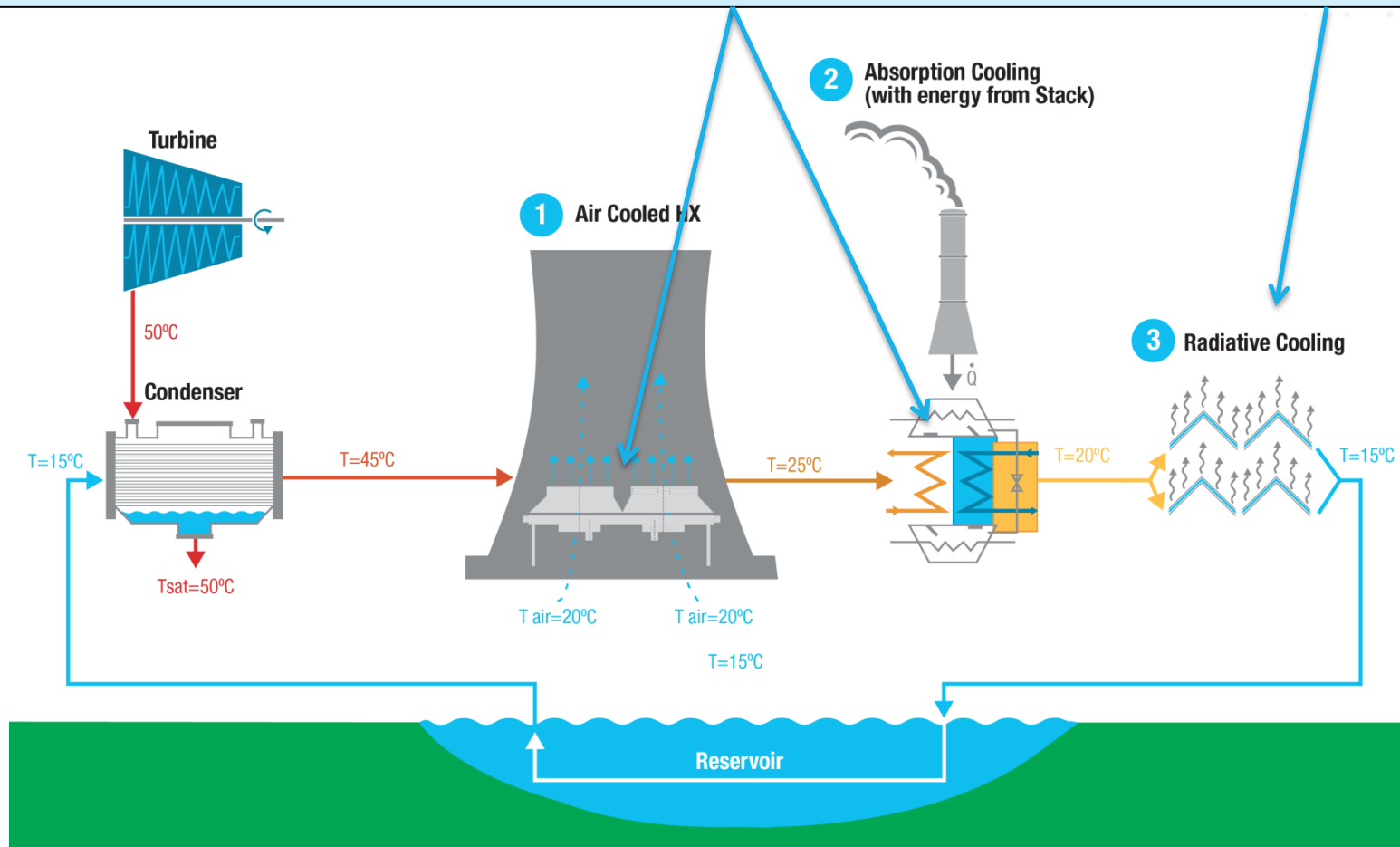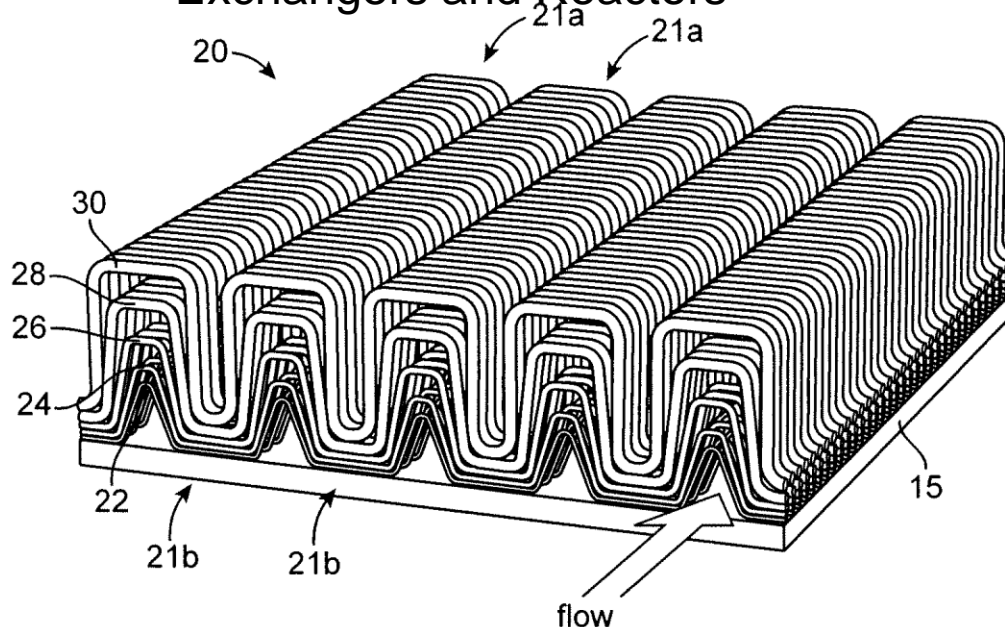
Proposed Performance Targets

Structures for Air Side Heat Transfer Enhancement

US Patent 20120261106 A1

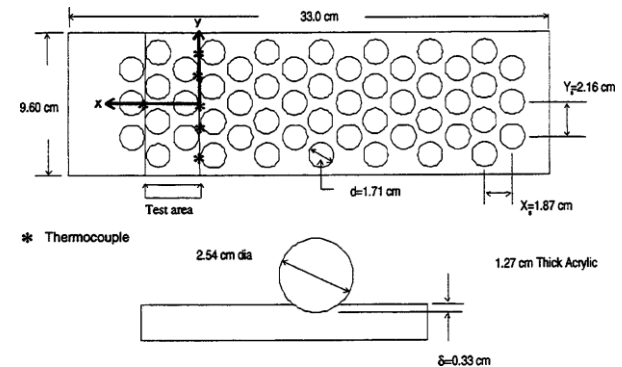Non-Isotropic Structures for Heat Exchangers and Reactors

Factor of 9 increase in volumetric heat transfer claimed with 1/3 the pressure drop compared with conventional radiator

John Kelly, Altex Technologies, 2012

Heat transfer augmentation for flow through channel with dimpled surface

For Re=1000, $Nu/Nu_{smooth} \sim 2.1$
$f/f_{smooth} \sim 1.5$

3D Printed HX

Challenge to Thermal Engineering and Manufacturing Communities

Reimagine how an air-cooled heat exchanger is configured to give significantly higher heat transfer rate and reduced pressure drop

    a. high fidelity CFD tools to guide flow paths and wall structures

    b. highly scalable designs are essential to meet programmatic goals

    c. low cost materials of construction

Identify manufacturing techniques that are available or need to be developed to enable the low cost fabrication of the heat exchanger

    a. additive manufacturing

    b. ultrasonic welding

    c. high temp brazing, vacuum brazing

    d. precision stamping

    e. laser milling

Bridging the Gap

Thermal Engineering
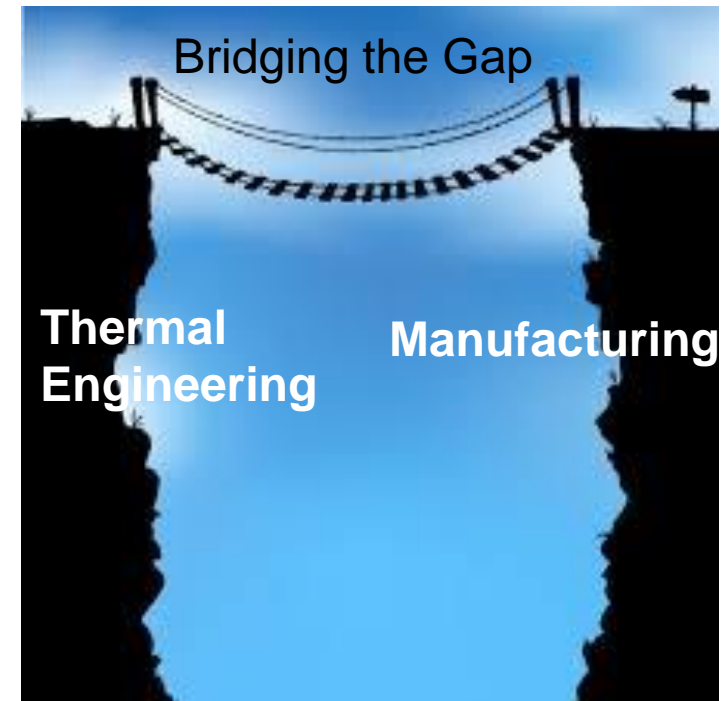
Manufacturing

●**Encourage team building between Thermal Engineering and Manufacturing communities**

Transformative Advancement in Air Side Convection
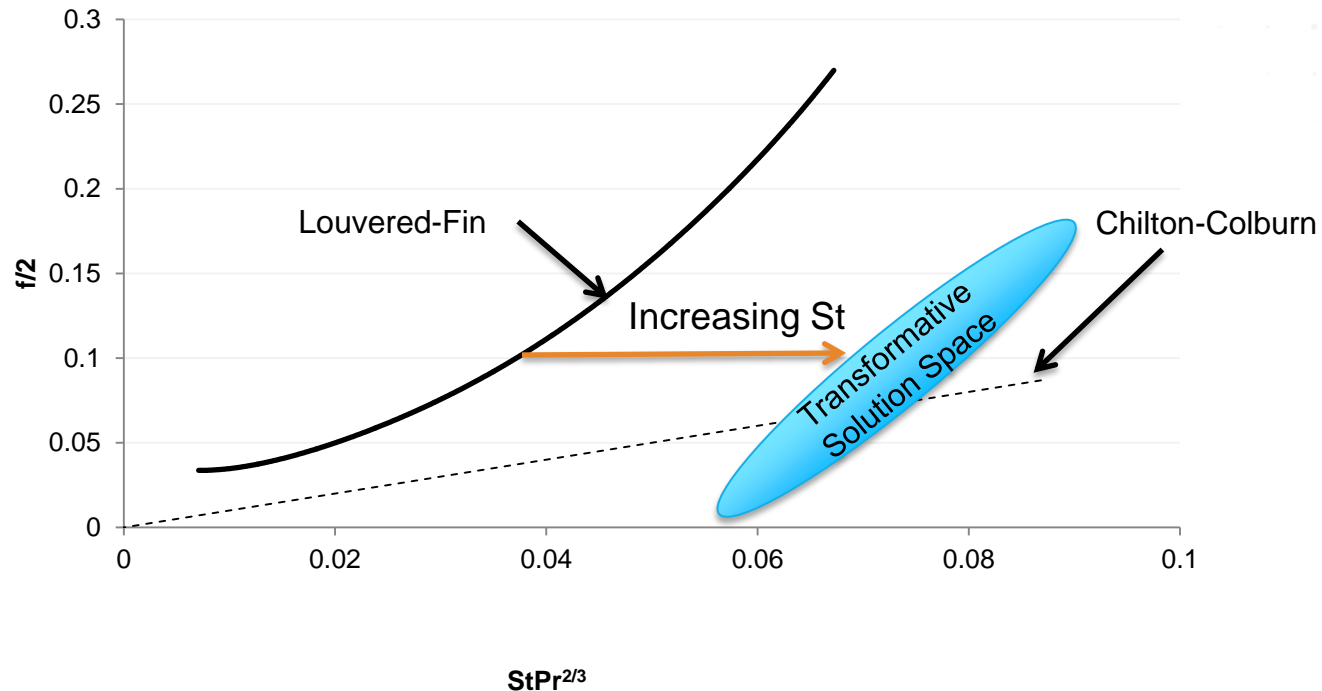
$$St = \frac{h}{\rho U C_p} \qquad \frac{f}{2} = \frac{\tau_w}{\rho U^2} \quad \text{(Fanning)}$$

ARPA-E Heat Exchanger Design and Technoeconomic Analysis

No Design— pressure drop assumed

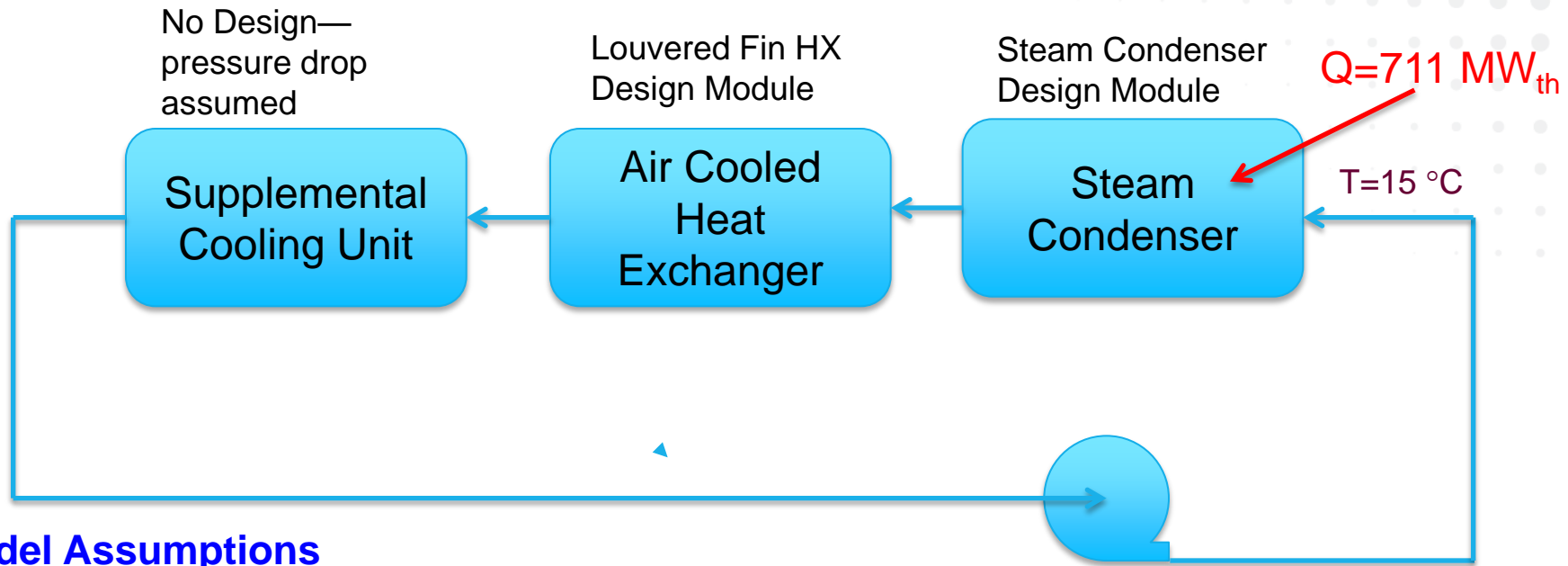Louvered Fin HX Design Module

Steam Condenser Design Module

$Q=711$ MW$_{th}$

T=15 °C

Supplemental Cooling Unit ← **Air Cooled Heat Exchanger** ← **Steam Condenser**

Model Assumptions

- NETL Case 9 subcritical PC plant, 550MWe
- Use existing steam condenser (T_{sat}=38 °C; $T_{cold,\ in}$=15 °C)
- Original evaporative cooling system replaced by ARPA-E cooling scheme
- No changes to balance of plant operation
- 11,000 kg/s circulating water mass flow rate

ARPA-E Tough!

Is there a solution with no increase in LCOE?

Allowable Capital Cost for Supplementary Cooling Unit with No Change in LCOE & 2% Δ

Analysis Based on Standard Louvered Fin Air Cooled HX with Natural Draft Supplement

ΔLCOE=0

ΔLCOE=2%
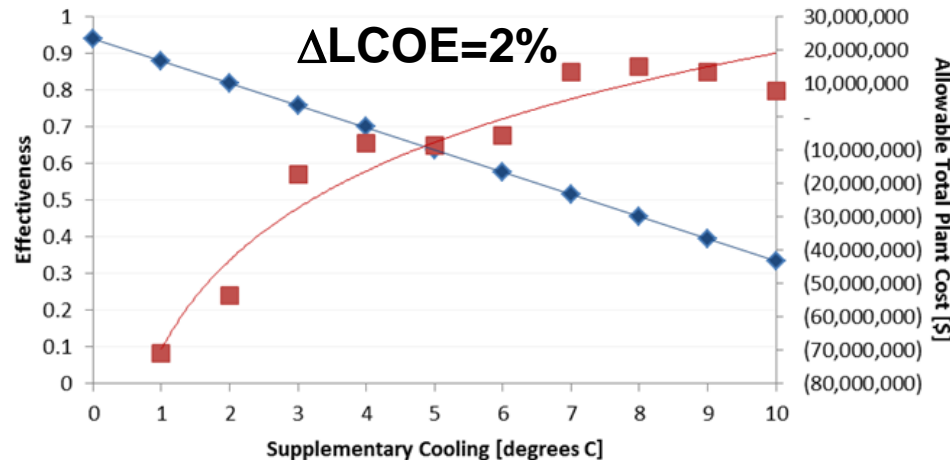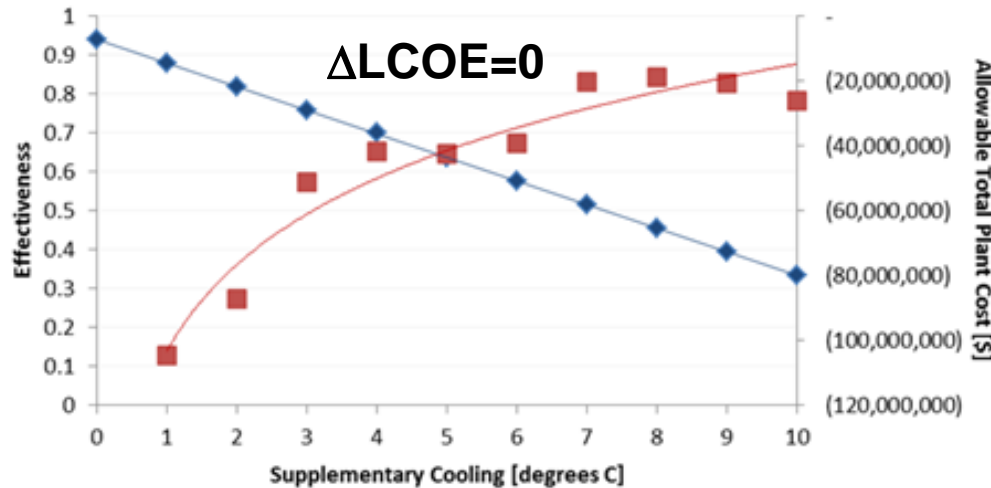
- ●With standard louvered fin design, and no change in LCOE, no solution exists where allowable supplemental cooling costs are positive

- ●**NOT REALISTIC!**

- ●Air cooled HX with reasonable Effectiveness will be least cost HT equipment; do as much cooling with air cooled HX as possible

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Allowable Capital Cost for Supplementary Cooling Unit and No Change in LCOE

Supplemental Cooling 4 °C

$St=kSt_{louvered}$ A:k=1, B:k=2, C:k=3, D:k=4, E: k=5, F=7, G=10
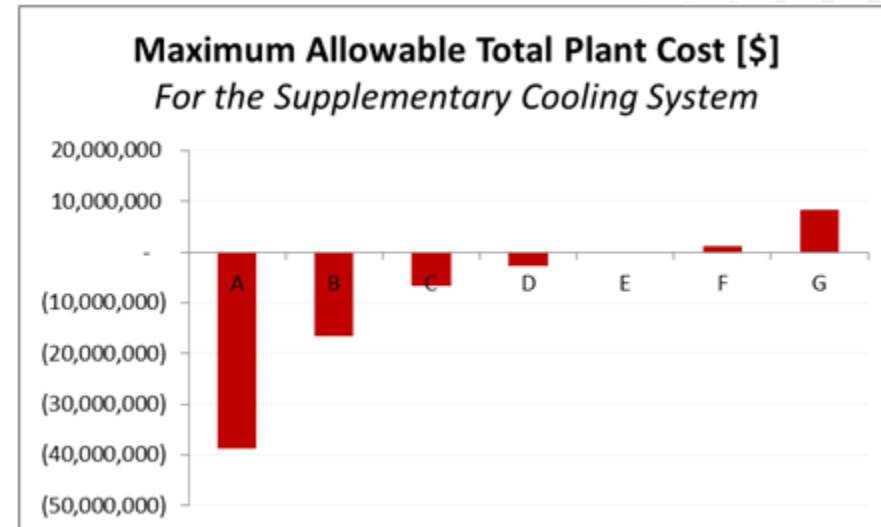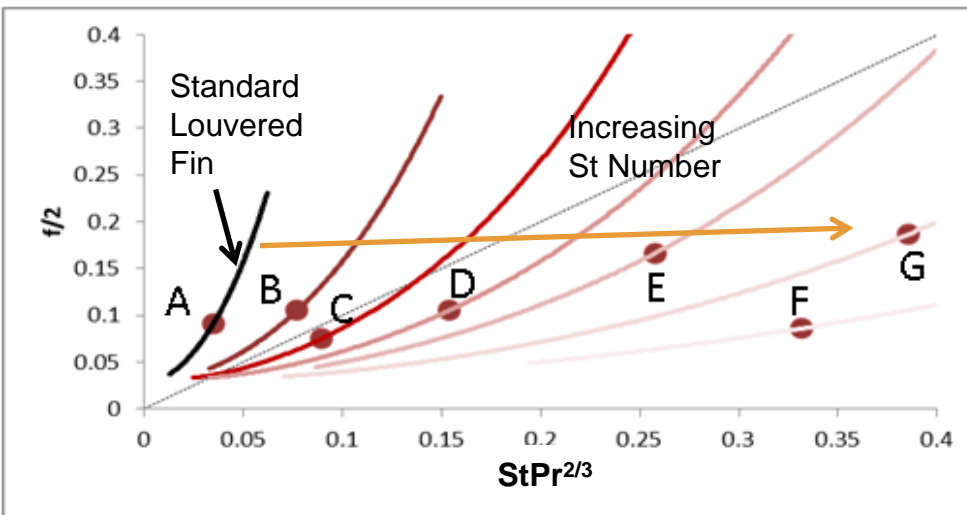
- Point G allows approximately $8 M for supplemental cooling or $50/kW$_{th}$

- In comparison air cooling HX, $47/kW$_{th}$ or $28/m^2

Allowable Capital Cost for Supplementary Cooling Unit and 2% Increase in LCOE

Supplemental Cooling 4 °C $St = kSt_{louvered}$ A:k=1, B:k=2, C:k=3, D:k=4, E: k=5, F=7, G=10
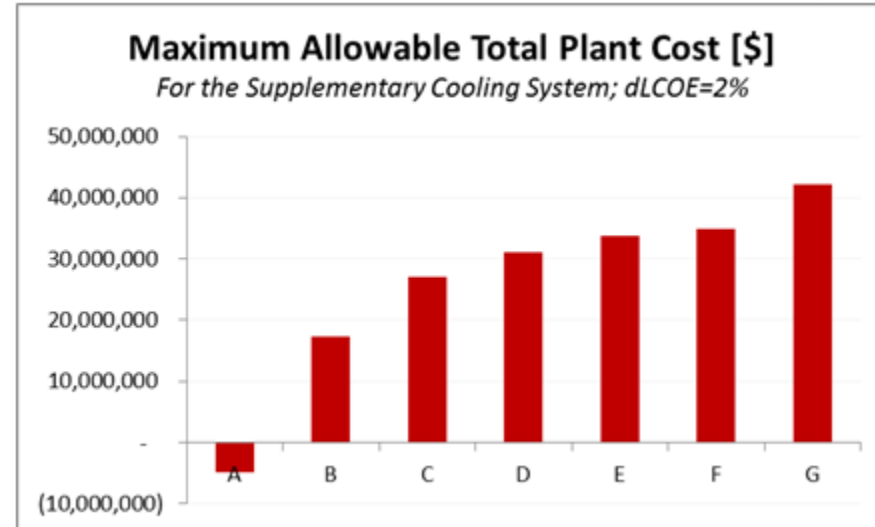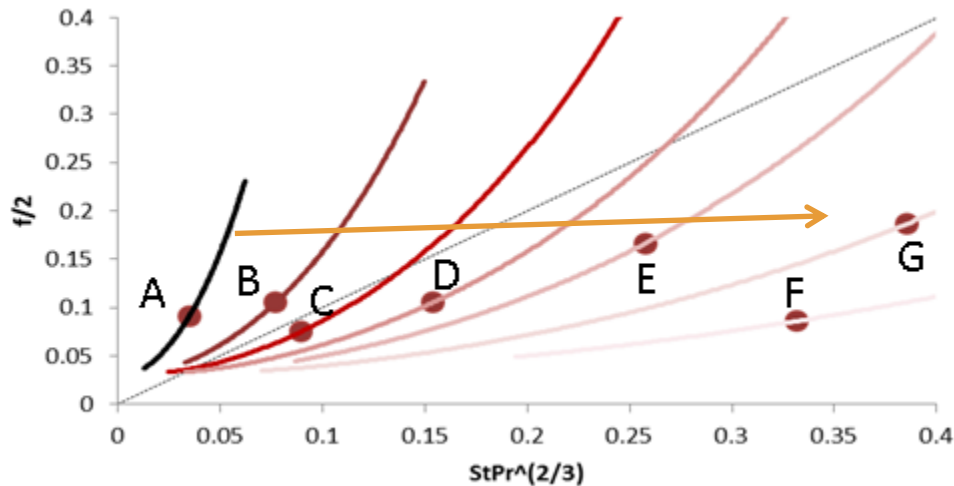
- Point E allows approximately $30 M for supplemental cooling or $150/kW$_{th}$

- In comparison air cooling HX, $47/kW$_{th}$ or $28/m^2$

Air Cooled HX Performance Metrics

I. $St > 5\{St\}_{louvered}$

II. Cost < $47/kW

Absorption Cooling with Waste Heat From Flue Gas

- **Heat capture from stack complicated by H2SO4 formation and possible CO2 capture**
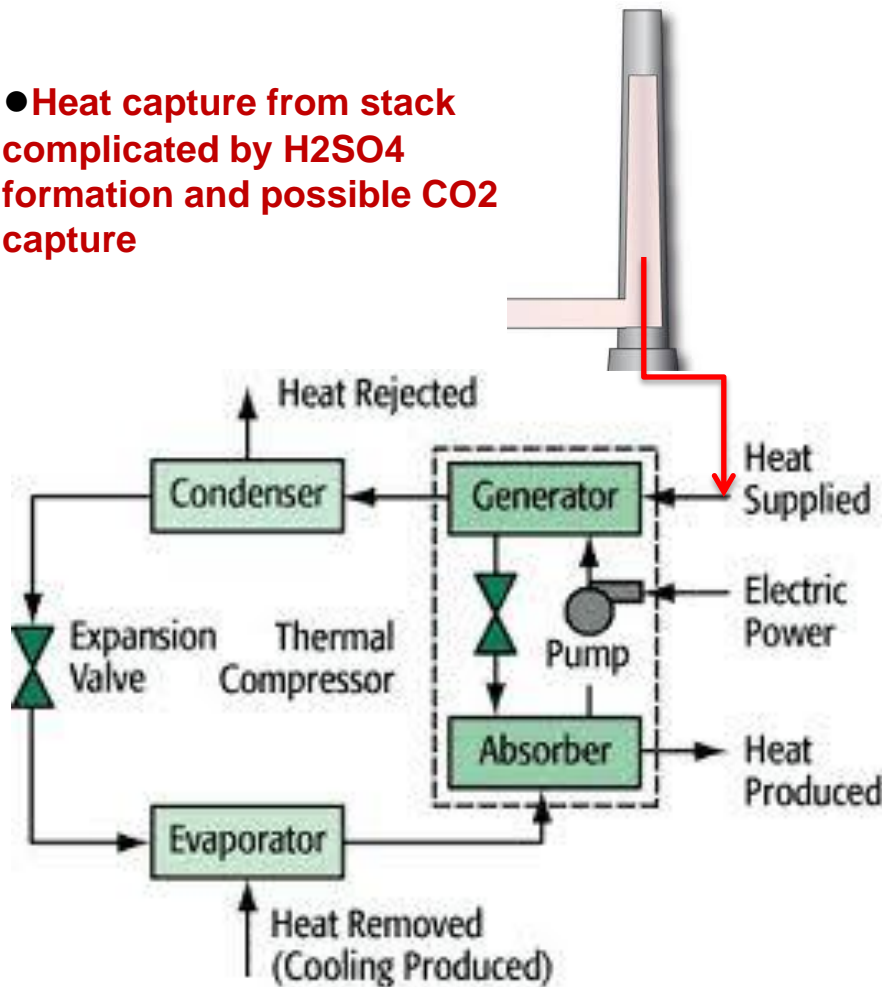
- 30-50 MW waste heat available in stack at T=170 °C, assuming a dew point of 150 °C (500 MW Plant)

$$COP = \frac{\dot{Q}_{cooling}}{\dot{Q}_{heat\ in} + \dot{P}_{parasitic}}$$

Performance Metrics

I.   COP>2

II. $T_{cold}<15\ °C$
     $T_{regen}<150\ °C$

II. Cost<$150/kW_{cooling}$

Surface Coatings to Create Selectively Specular Surfaces
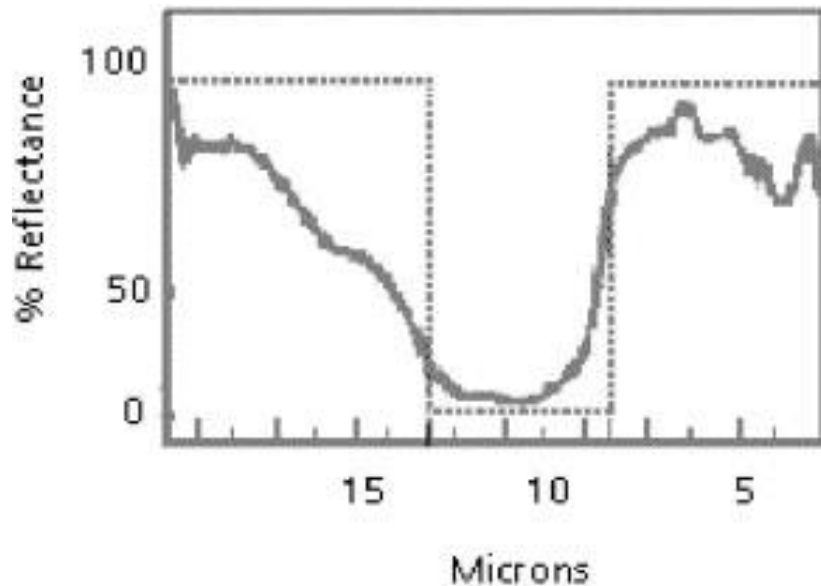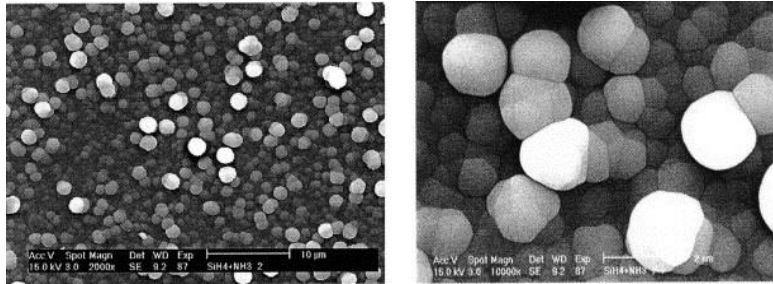
● Selectively specular surface created by depositing silicon nitride on aluminum

Liang et al., Solar Energy, 2002

Ideal Surface Coating

Visible

Ideal spectral reflectance

ρ_λ Spectral Reflectivity

1

0

1   40

λ Wavelength, μm
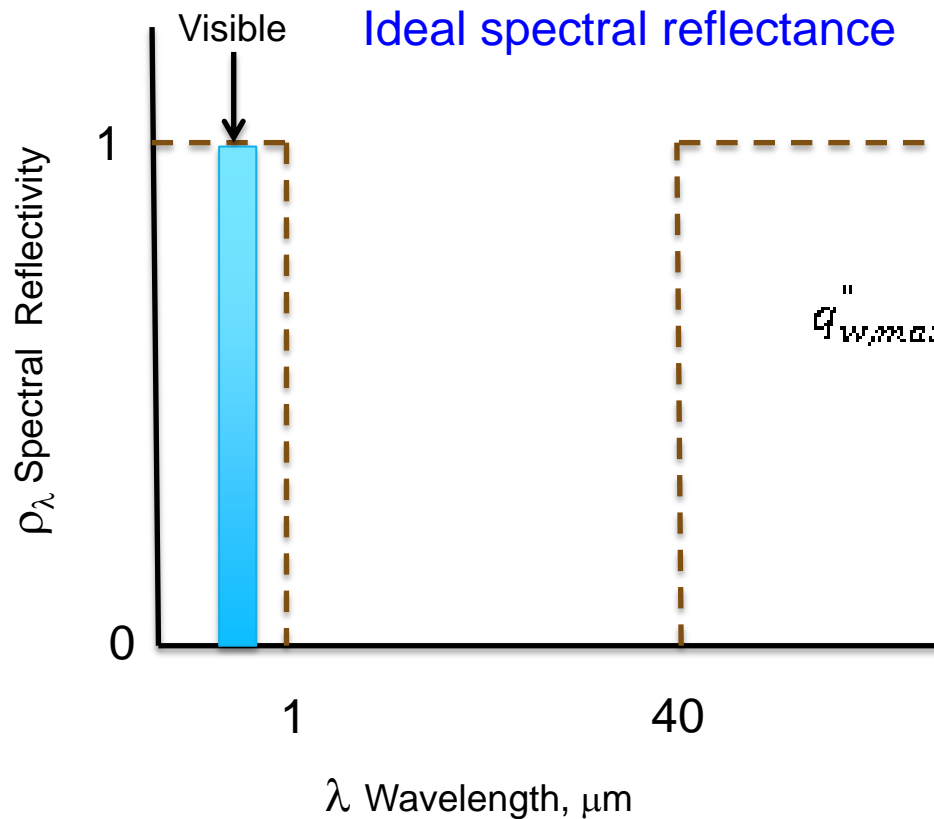
● Ideal surface absorbs and emits within infrared band and reflects all other incident radiation

$$q''_{w,max} = \int_{\lambda 1}^{\lambda 2} \varepsilon_\lambda E_{b,\lambda}(T_1)\,d\lambda - \int_{\lambda 1}^{\lambda 2} \alpha_\lambda E_{b,\lambda}(T_2)\,d\lambda$$

$q''_{w,max} \sim 260 \text{ W/m}^2$

*Assumes no convection at the surface
T1= 20 °C
T2= -50 °C

Low Cost Sky Radiator

Solar Shade

Water Out

Selective Specular Reflector

Radiation To Sky

Frame

Casing

Water In
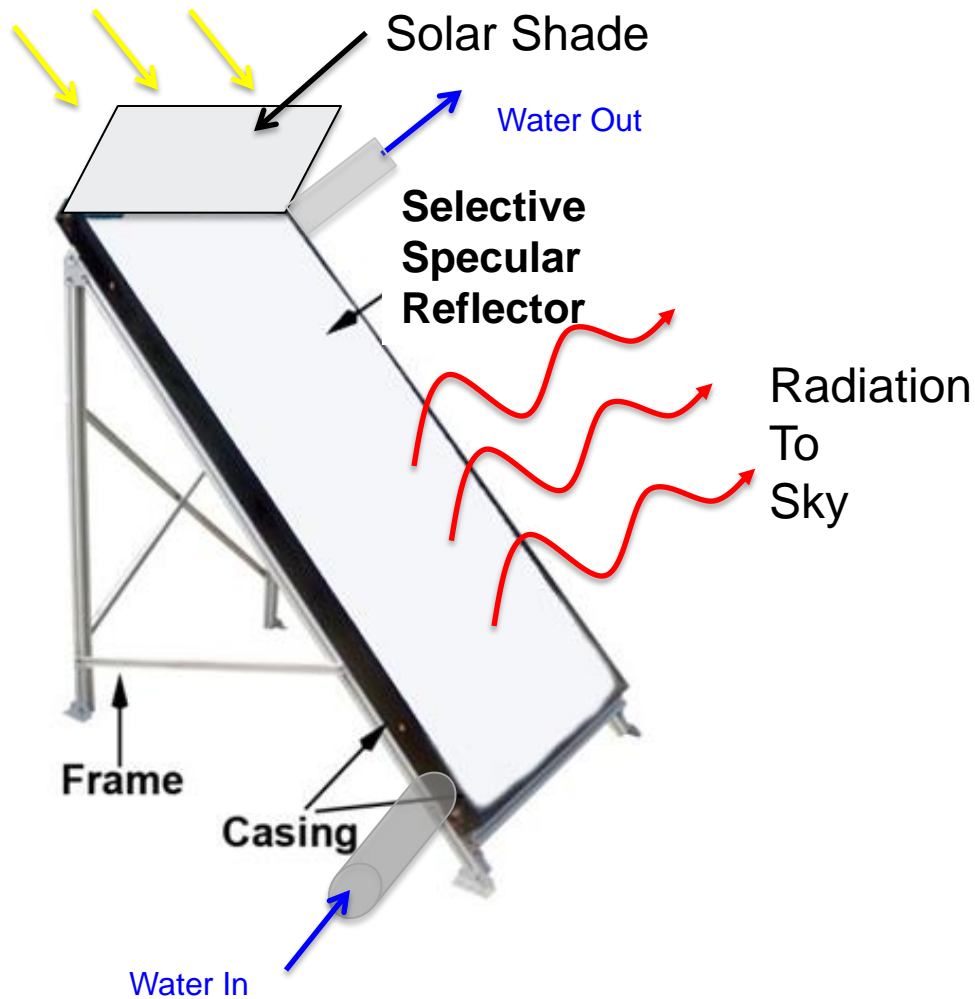
●To dissipate 60 MW with $\Delta T = 5°$ C, 48,000 2 x 4 m^2 radiators required

Performance Metrics

I. Heat Flux q">150 W/m^2 daytime

II. Heat Flux q">200 W/m^2 night time

III. Cost<\$30/m^2 (economies of scale to aid low cost constraint)

Efficient Forced Draft Air Pumping

Variable Pitch/Variable Speed Fan
Technology

Performance Metrics

I. Fan Efficiency η_{fan}>80% over full
range of flow rates and fan speeds

II. Cost<$265/m^3/s full capacity

Can Coatings of HT Surfaces Prevent Corrosion and Fouling?

High speed soap coating of nanomaterials

▸ Vacuum-free, atmospheric method to deposit materials from solution

  – 1.2 m of material/s coated with 4 nm thickness
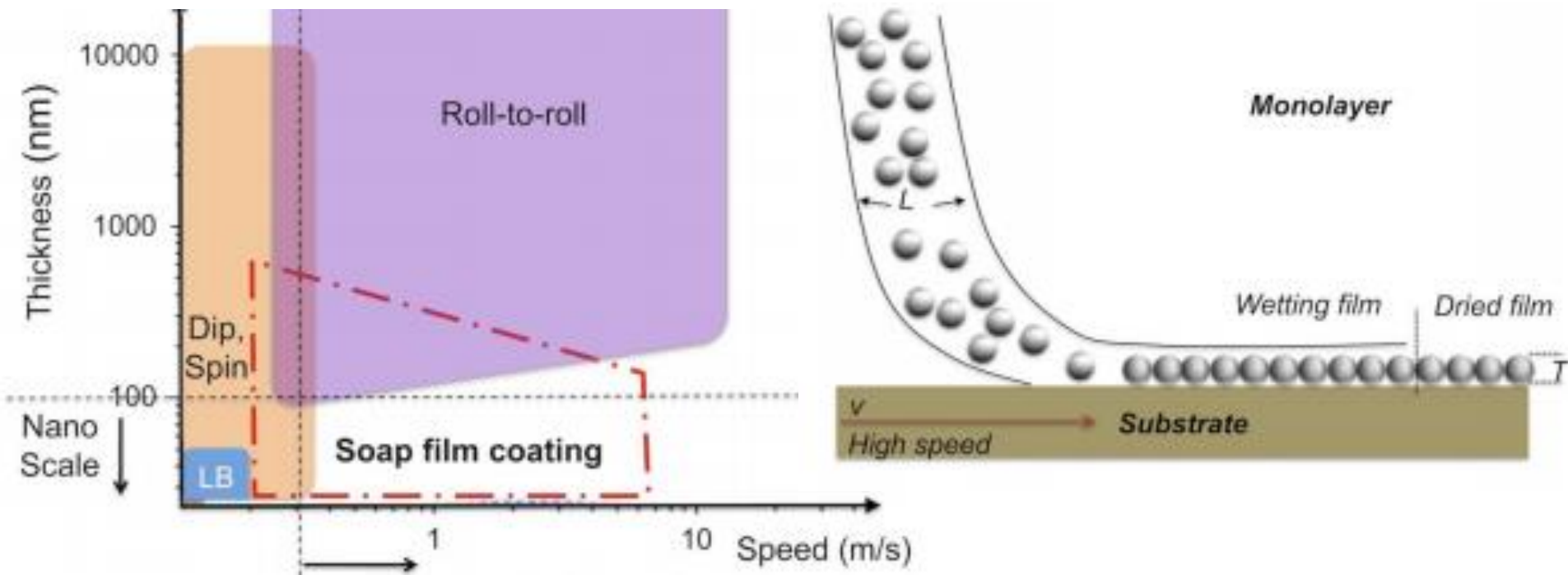
ARPA-E Funded Direct Contact Air Cooling with Hygroscopic Fluid - EERC North Dakota; Open FOA
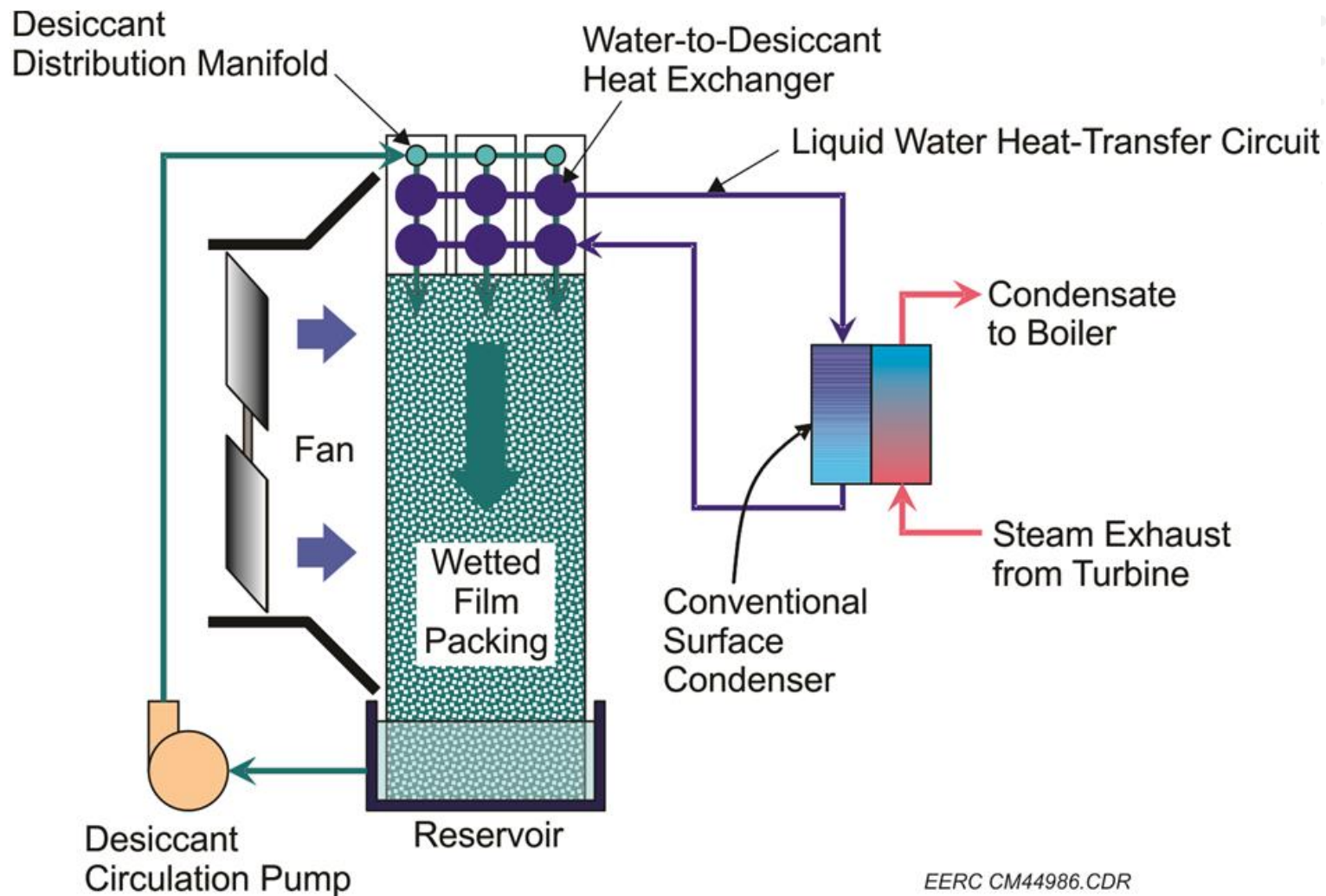
EERC CM44986.CDR

100 kW Prototype Testing Requirement

Requirement for Prototype Testing

●All ARPA-E thermal performance requirements must be demonstrated at a scale of **100 kW** or greater

3-D Printed Heat
Exchanger

ARPA-E Program Merit Questions—Analogous to DARPA Heilmeier Questions

I. What is the problem is to be solved?

II. If successful, how will the proposed program advance the ARPA-E mission? Why will it matter?

III. What are the program goals and how will progress towards those goals be measured?

IV. What is the current state of R&D in this area and how is the proposed program approach transformative and disruptive relative to that state?

V. What are the critical scientific and engineering breakthroughs needed to assure program success?

VI. What research communities need to be brought together to create research teams to address the program goals? Is there a critical mass of experts to make the program successful?

Let's Have a Productive Workshop!

●Use this opportunity for networking and team building

●Competitive teams will have expertise in both thermal fluid engineering and manufacturing

●Use this opportunity to guide high level programmatic framing of the problem
> 1. Is ARPA-E targeting the appropriate performance metrics?
> 2. Ideas on how to use techoeconomic analysis

●What scientific, engineering, and technology advances are required for programmatic success? Cordial frank debate is encouraged!

●Do you have any new ideas that can meet programmatic goals that have not been discussed?

●Please do not waste time telling ARPA-E we are CRAZY; it is already well documented

ARPA-E Exchange

www.arpa-e.energy.gov
https://**arpa-e**-foa.energy.gov

Challenges and paths forward

- Challenge 1: Lower heat transfer coefficient for air systems
- ARPA-E Approach: Target increase of 3X in air side heat transfer
  - Leverage advances in thermal science [EPRI/NSF program]
  - Combine with advanced manufacturing to realize new designs at low cost
- Effect: less area required, so capital and maintenance costs decrease

- Challenge 2: Dry bulb temperature vs wet bulb temperature
- ARPA-E Approach: Develop low cost cooling systems that can go downstream of the air cooled heat exchanger
  - Absorption cooling
  - Radiative cooling
- Effect: return water cooled to the design point, so no decrease in turbine performance

Result – air cooled systems have higher costs

Comparison of Dry and Wet sytems
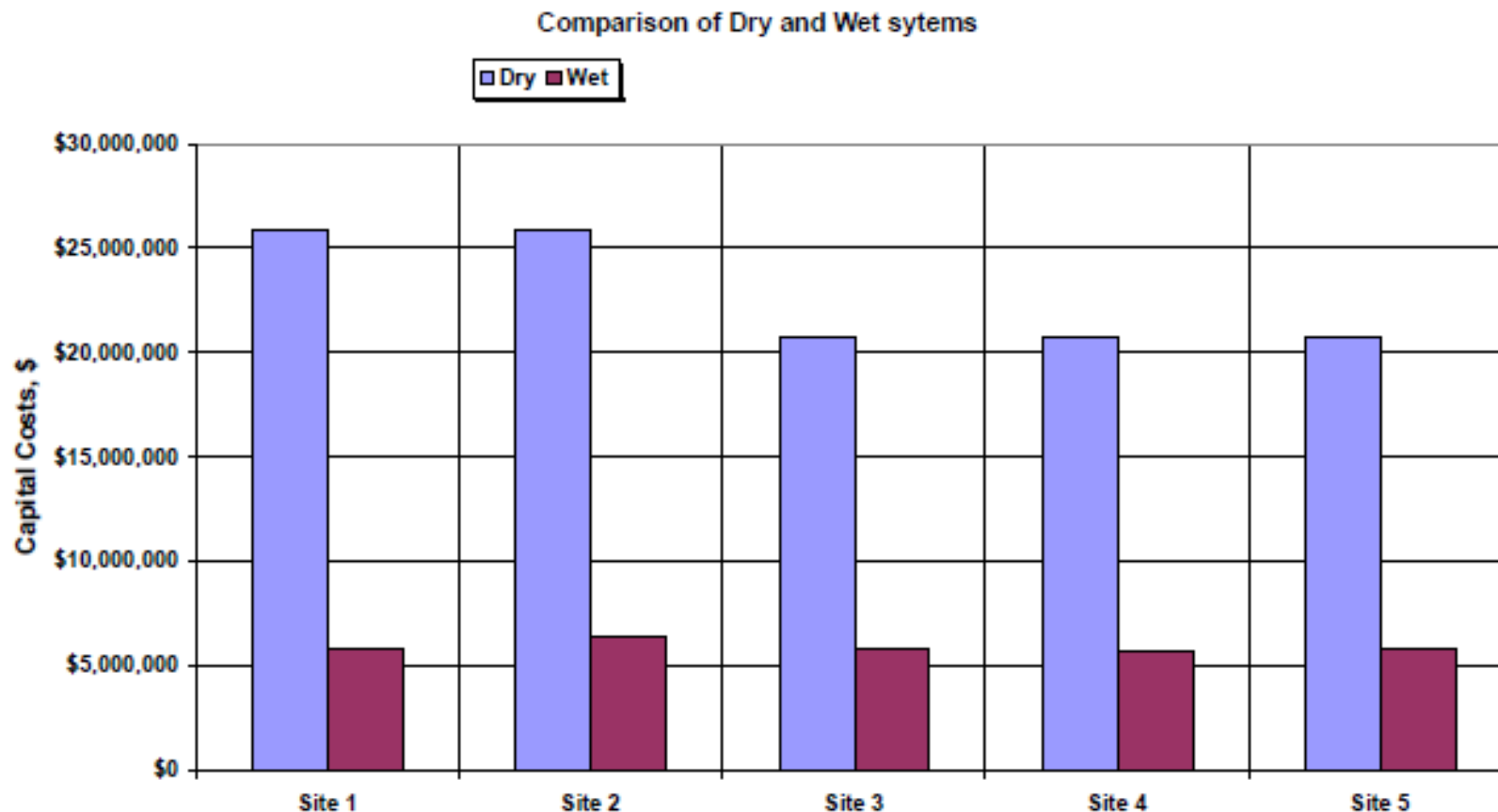
Temperature of the return water determines whether the turbine will experience backpressure

Comparison of wet vs dry bulb temperature for site 1

Condenser Temperature vs Turbine Backpressue for wet vs dry systems
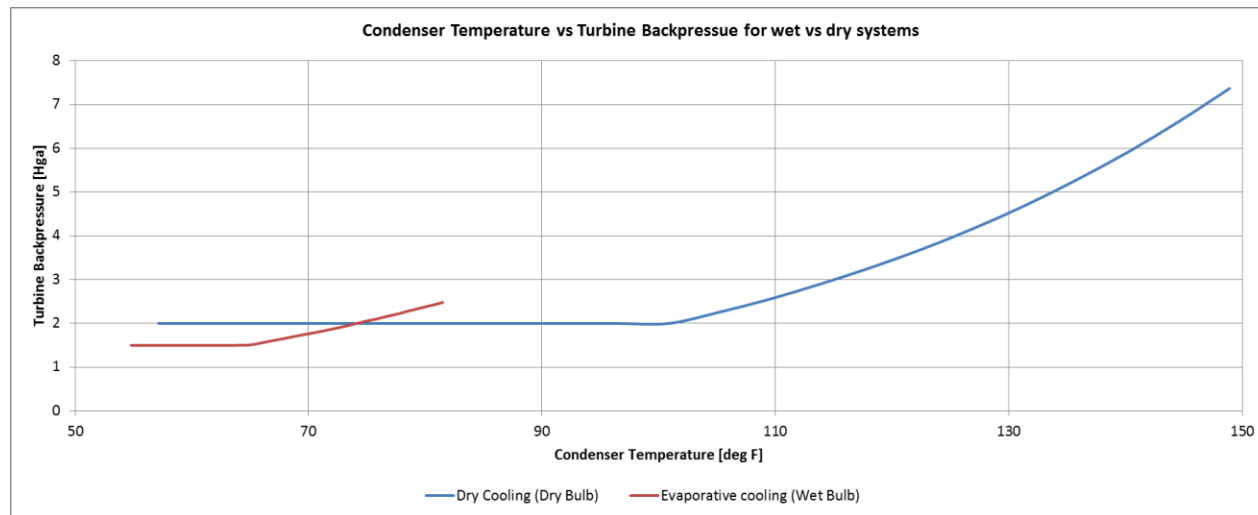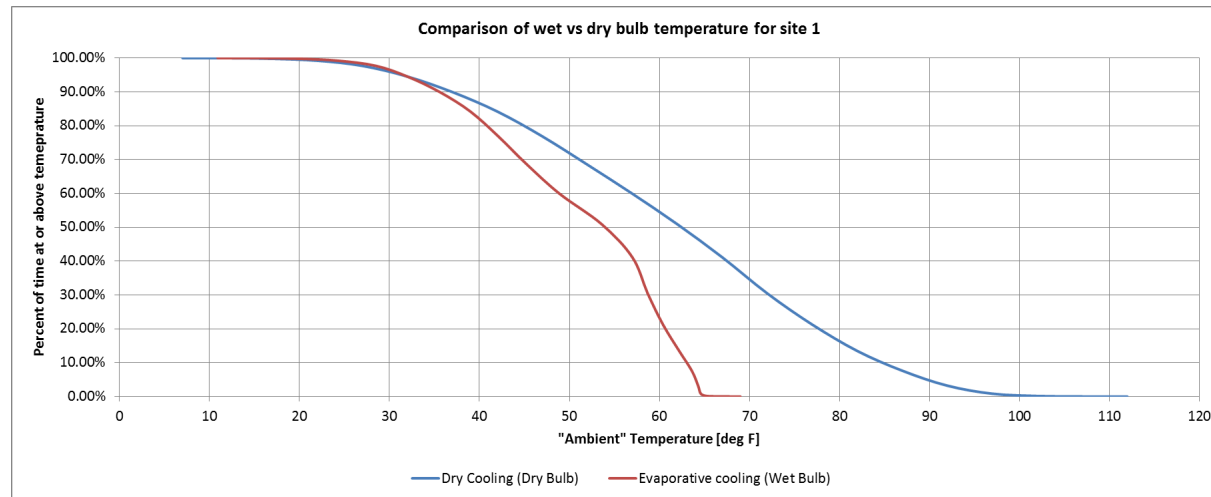
Previously funded work by DOE

Entity	Objective	Amount/$	Agency	Date
U. North Dakota	Air cooled device for power plants	472,586	ARPA-E	2012
Research Triangle Inst.	Develop and demonstrate an advanced, energy-efficient hybrid membrane system that enables the reuse of more than 50% of a facilities wastewater	4,800,000	EERE	2012

Pull out cooling ones

NSF/EPRI
NETL plans
NETL 1990's

Framing the opportunities – ARPA-E approach

Program vision
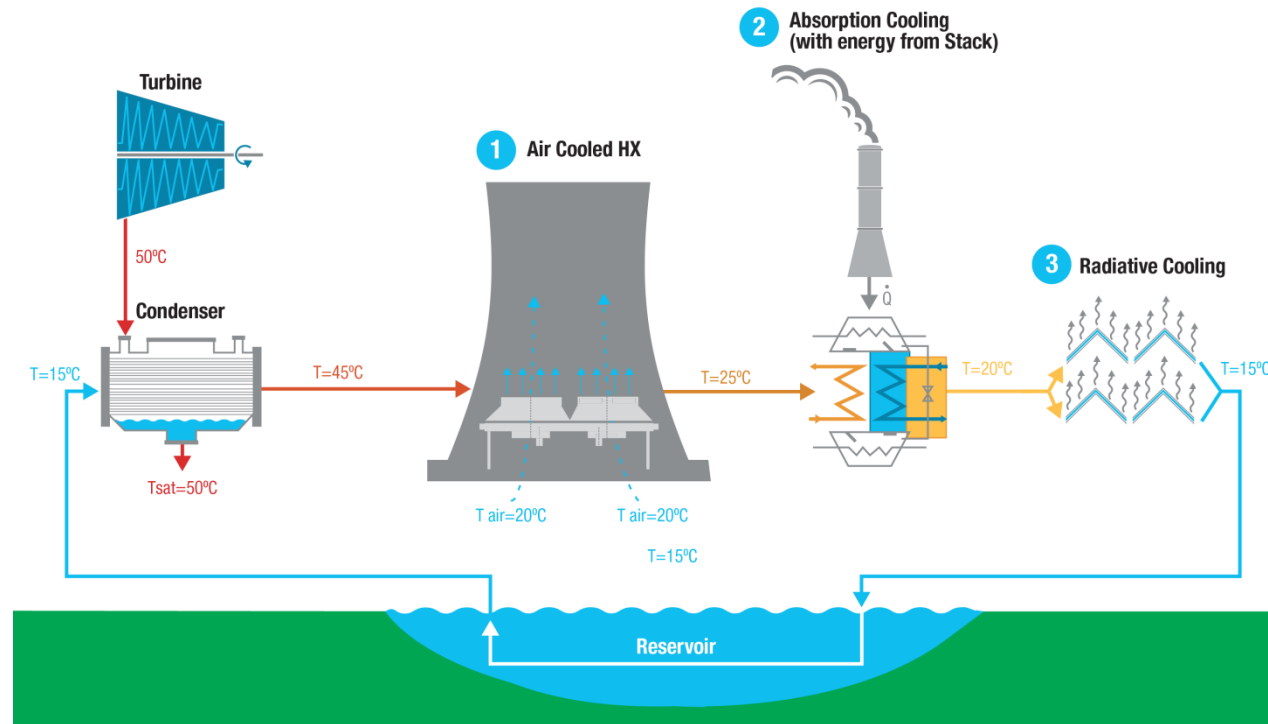
Retrofit cooling tower with ACHX

Develop downstream cooling technologies to get past dry bulb limit and avoid turbine backpressure

Where's the whitespace?
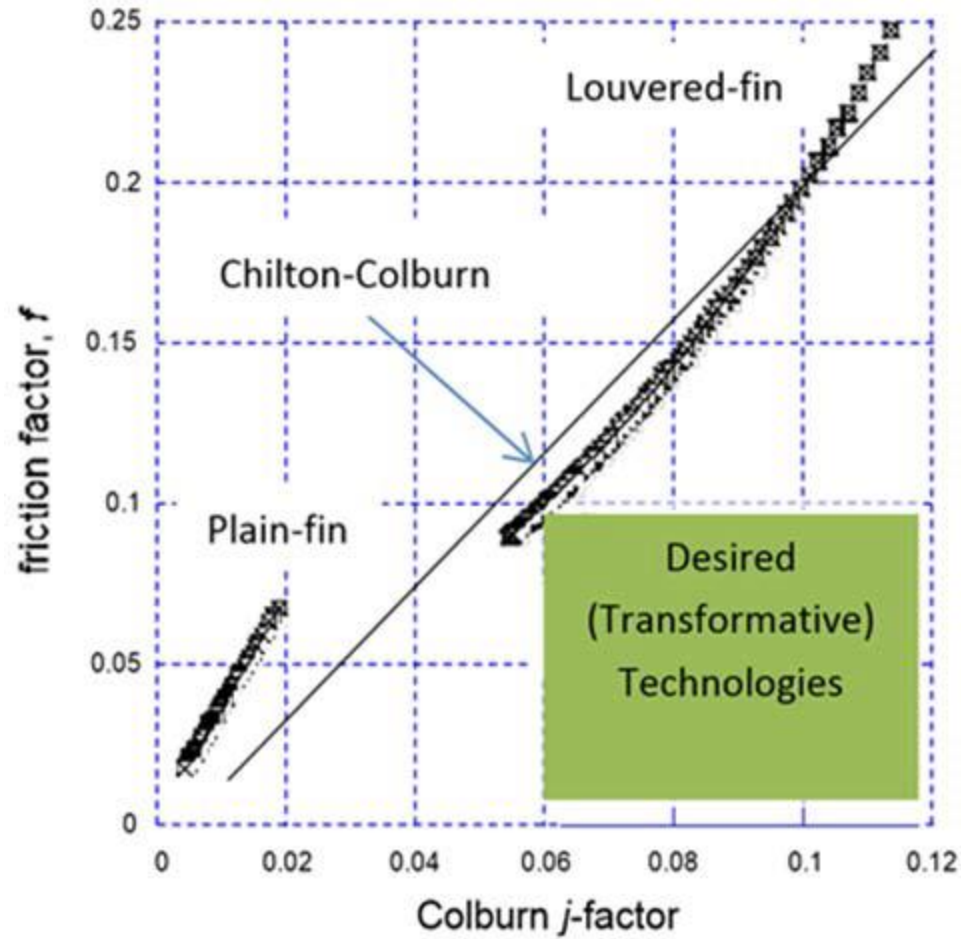
Our analysis demonstrates that this is feasible

This is probably several slides, and where we summarize the analysis we conducted across the various climates

And drives performance and cost targets in FOA

‣ More of our analysis, showing what the heat transfer coefficient needs to be to achieve energy/cost parity.

‣ How many more degrees would it have to be coole[r] downstream systems?

‣ What would their performance and cost need to be?

‣ Summary: if we achieve XYZ, this will become a viable and compelling option for power plants – and this is how we're setting targets

This is probab[ly] we summariz[e] acros[s]

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Quick side note – totally alternative approach which focuses on water recovery? (Seedling level efforts)

Sorbent water recovery. Depends if we can get numbers to work. Skeptical

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Sorbent vapor recovery analysis

‣ Concept: retrofit cooling towers to capture vapor with a desicant and use waste heat from the stack to regenerate the desiccant

‣ Energy-mass balance

‣ Economic

‣ Required

‣ Metrics ste

Sorbent water recovery. Depends if we can get numbers to work. Skeptical

CHANGING WHAT'S POSSIBLE

Summary of program goals and targets

‣ Advanced air cooling – heat transfer performance needed. Cost

‣ Downstream cooling – how many degrees? How much cost?
  – Radiative cooling
  – Absorption cooling

‣ Other track - water recovery from wet cooling systems?
  – Sorbents?

How are we going to do this? Sample technology plays from workshop

‣ Advanced air cooling

 – Microstructures to increase heat transfer on air side

 – High surface area thermally conducting metal foam polymers?

 – Ways to increase air speeds (via hyperbolic towers?)

 – Learning from engine cooling in aerospace industry?

 – Radiative cooling downstream

 – Absorption cooling downstream

‣ Water recovery from wet cooling systems?

 – Sorbents?

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Advanced air cooling

‣ Key is to get better heat transfer on air side. Better heat transfer = less surface area required = lower cost

‣ There is substantial work going on in the thermal transport community showing that adding microstructures to air-side heat exchange surfaces can significantly enhance heat transfer through generating vortices that trip the thermal boundary layer and promote mixing (voice track this and insert graphic)

‣ **ARPA-E play – leverage advanced manufacturing techniques (for example, additive manufacturing) to enable these advanced heat exchangers at lower cost.**

Example advanced air cooling – TBD

‣ Ari/Srinivas?

‣ HRL concept?

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HRL: 3-D manufacturing of advanced heat exchange surfaces

A. Collimated UV light, Photo-polymer waveguide, Photo monomer, Mask

B. Electroless plating

C. Polymer etch

D.

E.

Architectural elements

Lattice-based unit cell | Hollow-tube lattice member | Hollow-tube wall

Size scale	~ mm - cm	~ μm - mm	~ nm - μm
Controllable architectural features	Unit cell symmetry, spatial location of lattice members	Diameter, wall thickness, node geometry	Microstructure, multilayer, composition

- Manufacturing technique enables very high area/volume ratio

- While heat transfer properties are excellent, the pumping pressure loss is uncertain and needs to be understood

Absorption cooling concept

Radiative cooling concept

▶ Stanford coating?

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Program summary

FOA summary

‣ Areas of interest

‣ Metrics

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1. Some of our highest producing states will feel significant pain

The at risk plants here are from the more conservative, freshwater-only cooled systems

Legend:
- % of total US production low to no risk
- % of total US production at high/extreme risk
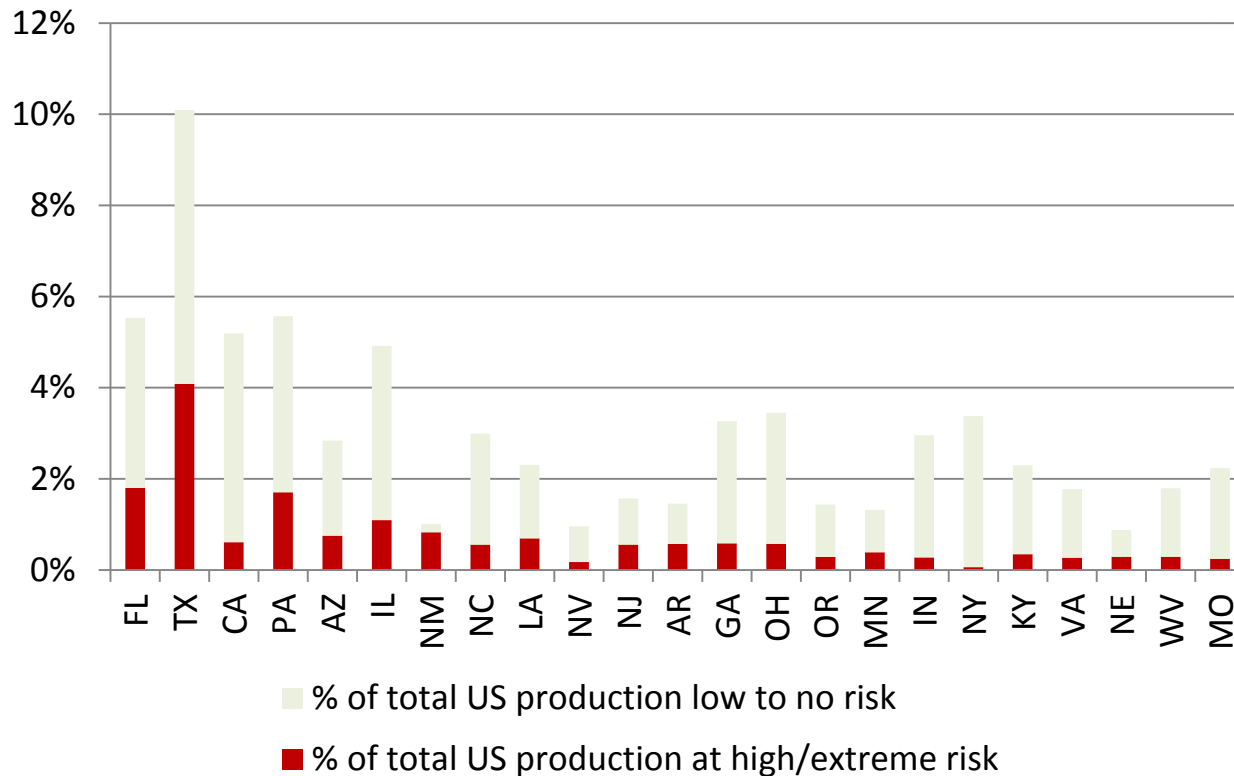
- My analysis does not yet consider projected plants – this is only existing production
- I could generate this for the case that includes lower quality water as well – up for discussion

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EPRI study background

‣ Rates of water use (gal/capita) in the domestic sector remain at their 2005 levels in each county

‣ New electricity generation follows EIA predictions (EIA, 2009).

‣ Population in the U.S. in 2030 is 32.4% higher than 2000 (Census Bureau, 2008). (0.94%/yr)

‣ **No climate change considered**

‣ Changes in water use occur primarily in two sectors: municipal/domestic & TE
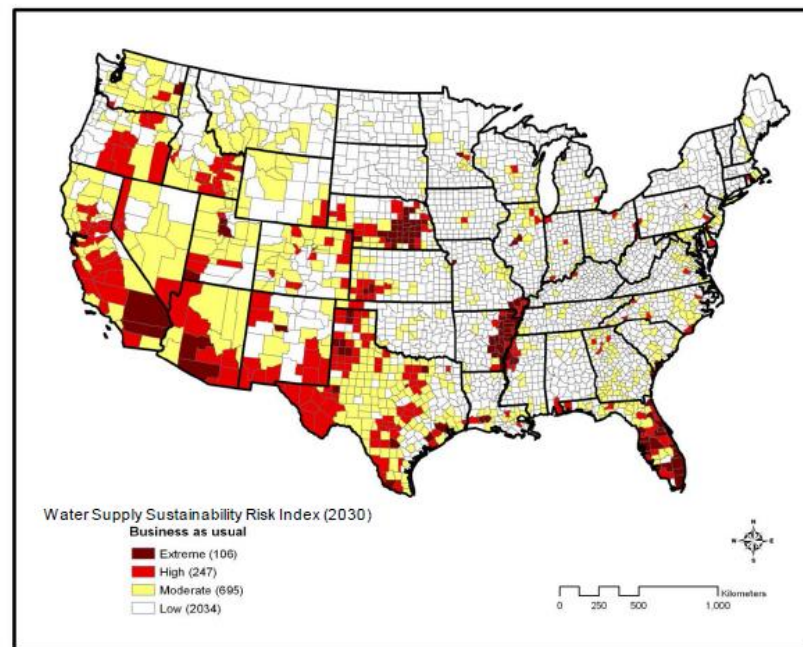
Risk Criteria for 2030

– >25% of available precipitation is used

– Groundwater withdrawal vs total withdrawal
   >25% (based on current groundwater withdrawal)

– Summer deficit >10 inches, and this water requirement must be met through stored surface water, groundwater withdrawals, or transfers from other basins.

– 2030 freshwater withdrawal is >20% higher than 2005 level

– 2030 Summer deficit is >1 higher than 2005

Water Supply Sustainability Risk Index (2030)
Business as usual
Extreme (106)
High (247)
Moderate (695)
Low (2034)

Figure 5-9
Water supply sustainability risk index.

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1. Northeastern data to add climate change effects, and allow us to analyze pump/treat

Modeled various combinations of population growth & climate change scenarios to predict future water issues

Water Supply Sustainability Index (2050)

- Extreme (412)
- High (608)
- Moderate (1192)
- Low (897)

Gaps:

- Data is not in readily accessible format (ArcGis)

- Temporal resolution is too coarse (decadal avgs)

- Supply not directly compared with demand

- Uncertainty not well defined

- Excesses not shown
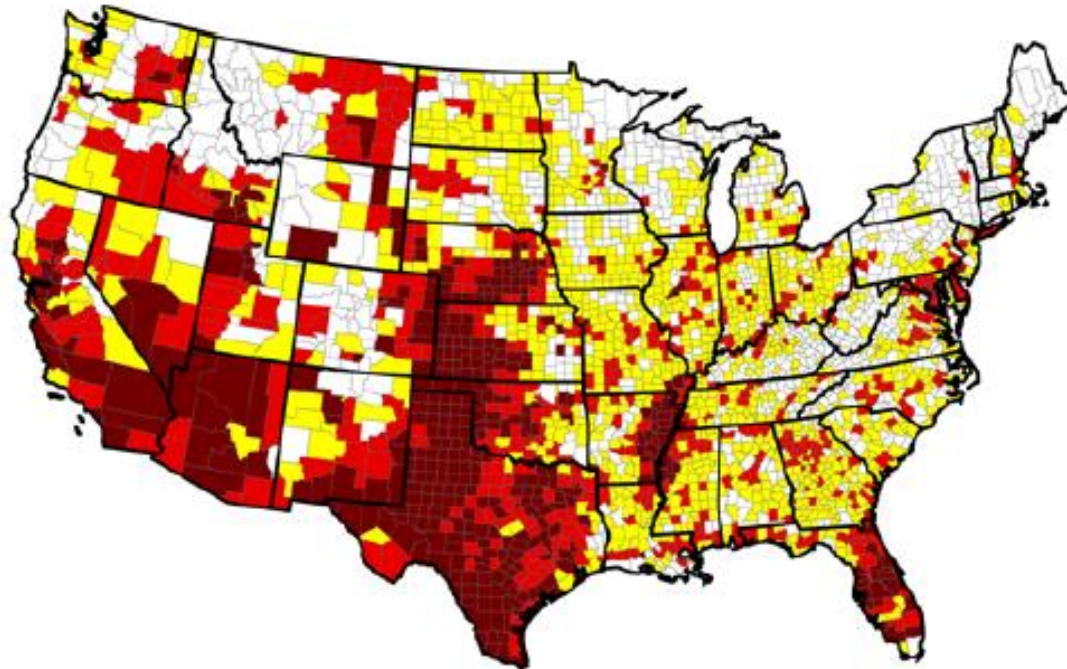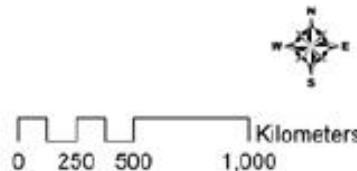
Parish, E. S., Kodra, E., Steinhaeuser, K., & Ganguly, A. R. (2012). Estimating future global per capita water availability based on changes in climate and population. Computers & Geosciences, 42, 79-86.

Vulnerability assessed now
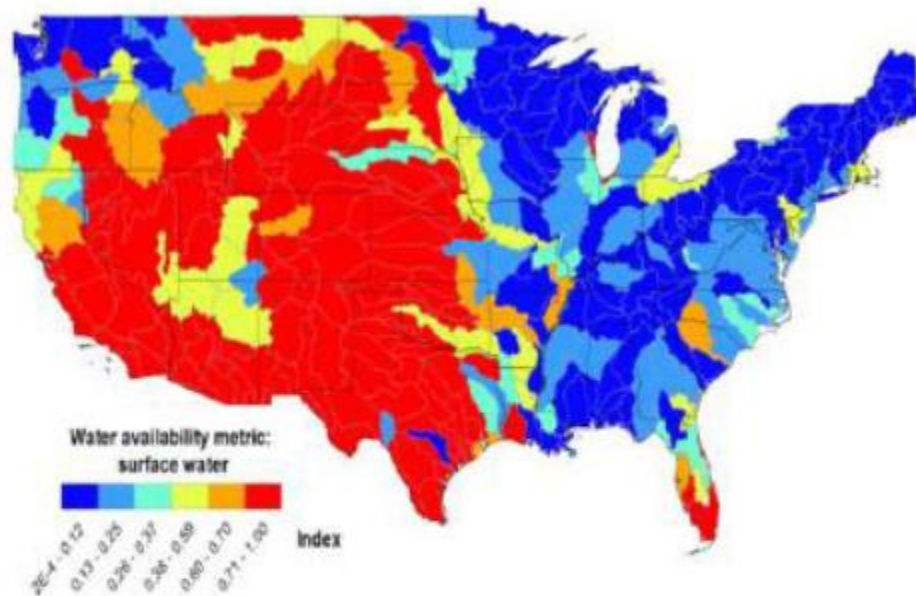
Figure 2. Drought vulnerability mapped at the 6-digit HUC level, the metric is based on the ratio of water demand to water supply (equation 1). Higher metric values (≥ 0.7) indicate regions most vulnerable to drought.

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Cooling system constructed (cumulative)
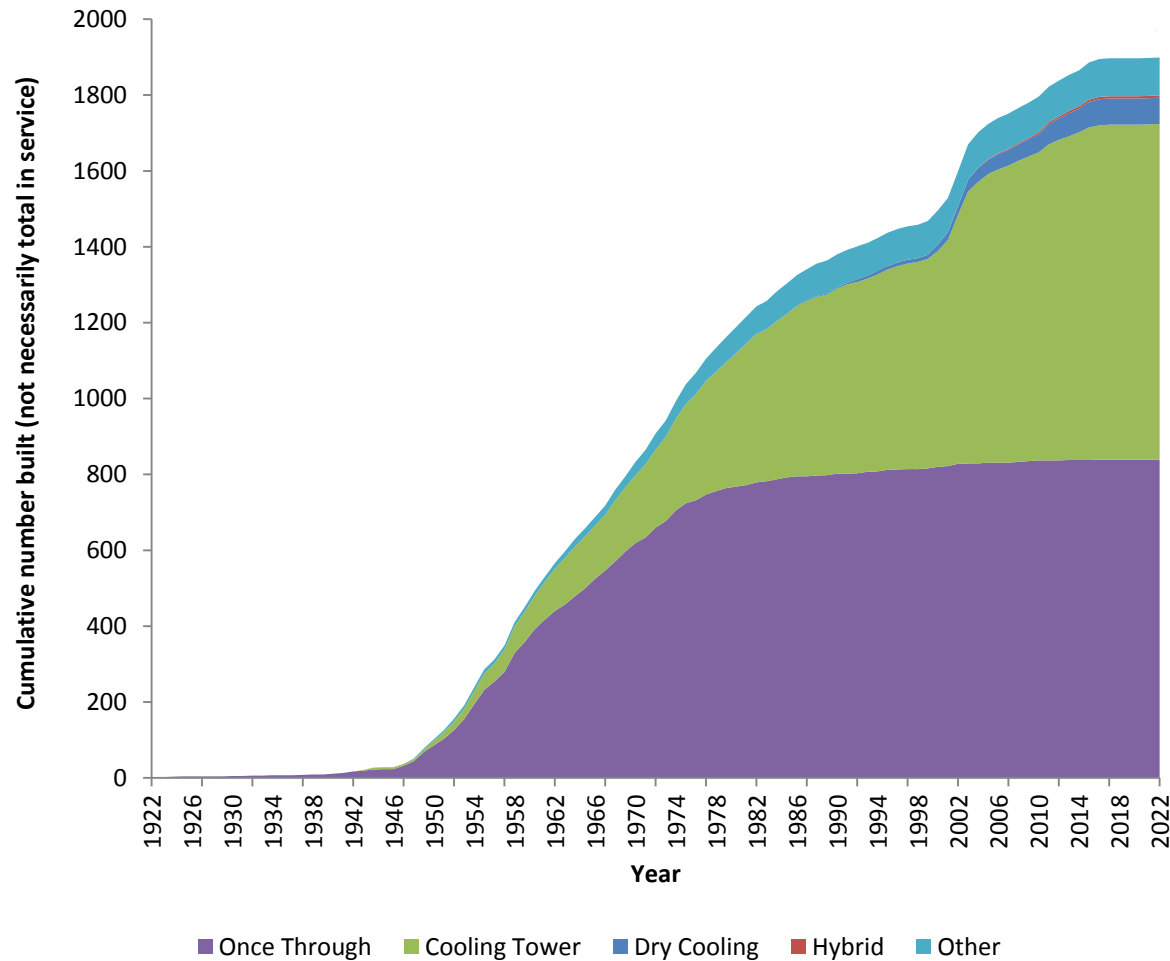
9. Distribution of systems
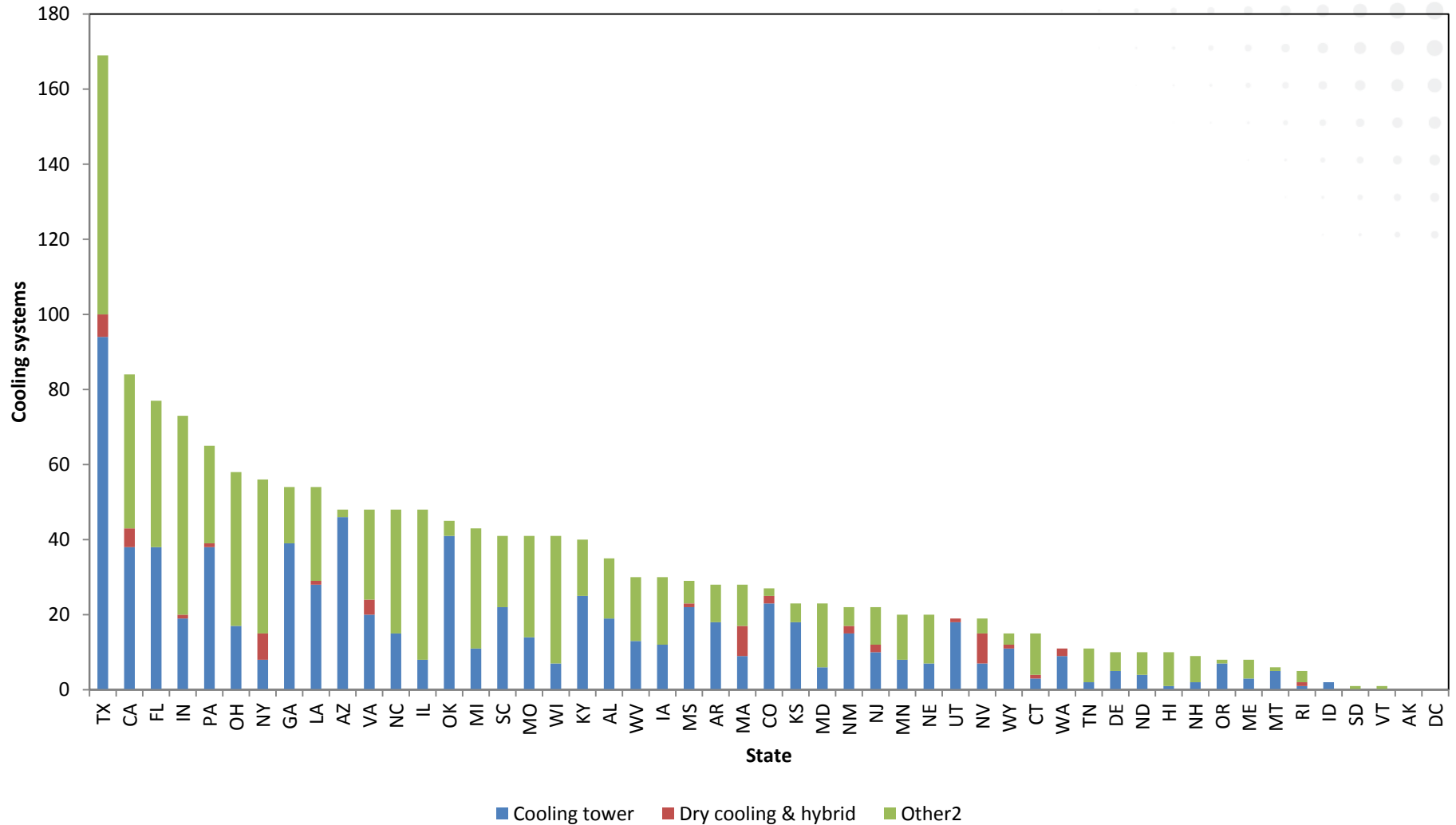
9a1. EPRI- plant types, sizes in US

Could use data with NE study to project production at risk
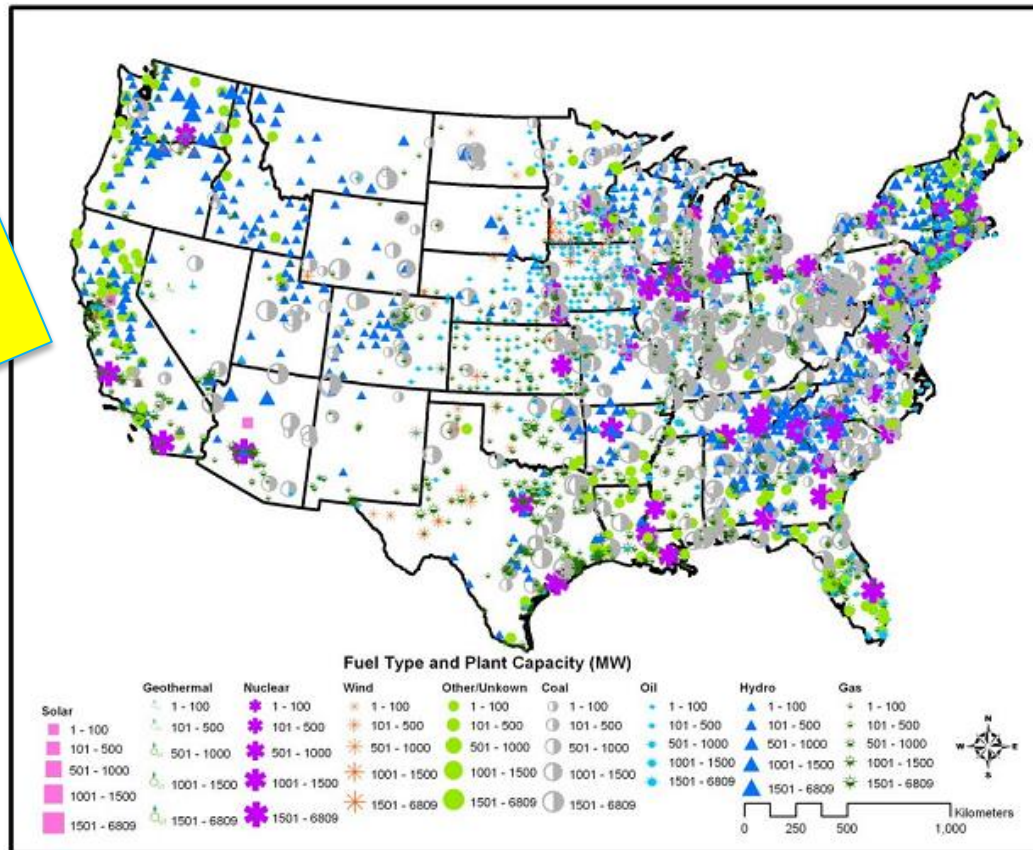
Figure 2-7
Fuel types and generation capacities of electric power plants in the U.S.

9a2. EPRI – new plants through 2030

Could use data with NE study to project production at risk
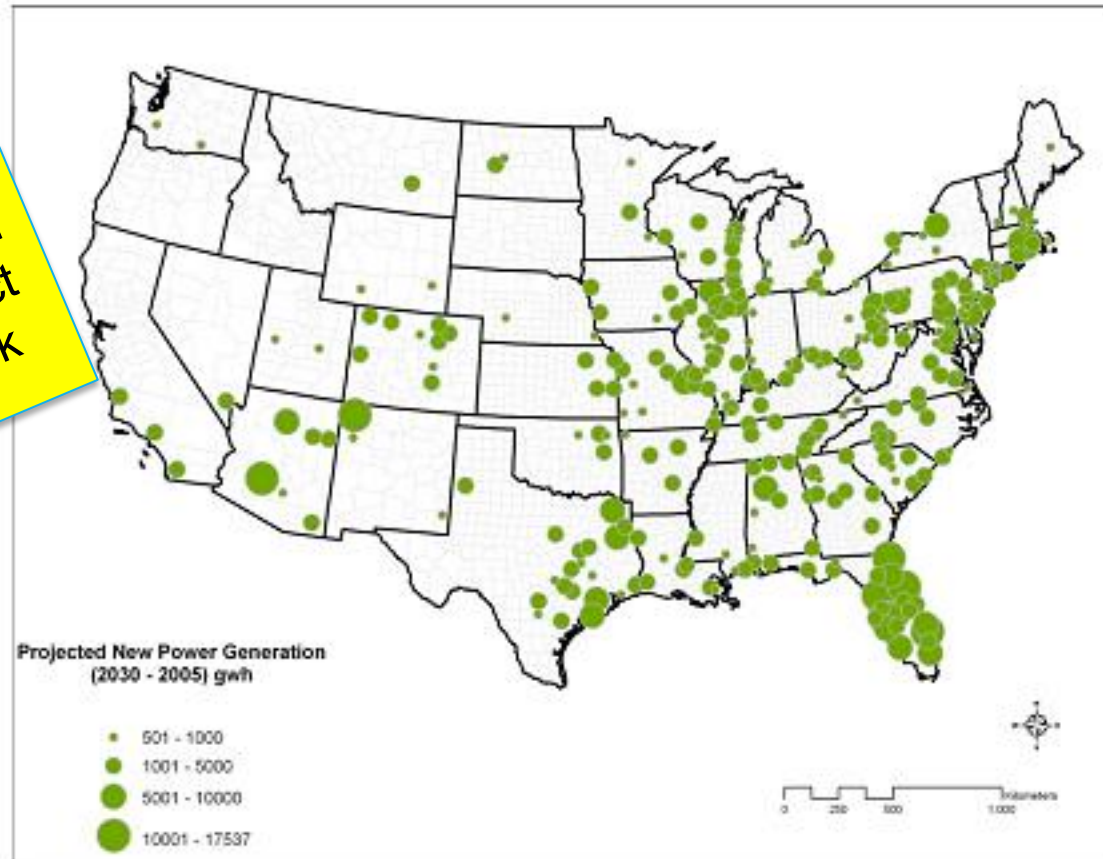
Figure 4-6
Projected new thermoelectric power generation between 2005 and 2030 at the county level, estimated based on EIA projections at the EMM level.

9a3. DOE Report – TE plant location and cooling type

Could use data with NE study to project production at risk

Water Type
- Fresh (blue)
- Saline (orange)

Cooling Type
- Cooling Pond
- Once Through
- Recirculating
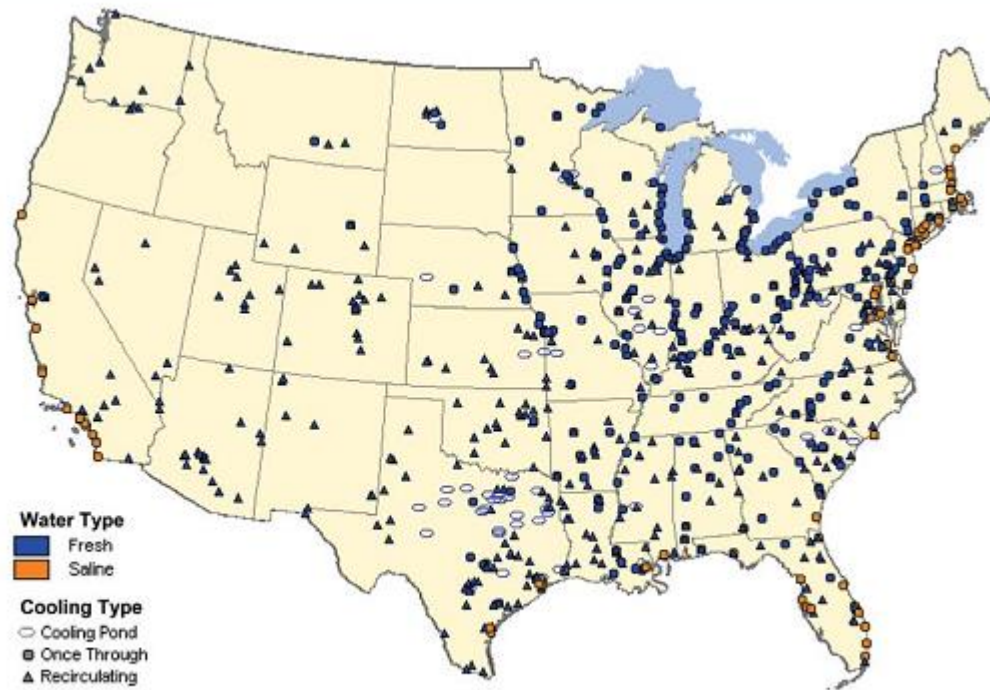
Figure 12. Locations of thermoelectric power plants by cooling technology and water source
Source: Adapted from NETL 2008

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9b. EPRI - Water withdrawals for thermoelectric generation (fig 2-5b)

Could use data with NE study to project production at risk

Thermoelectric - power Withdrawals
2005 (mgd)

- 0
- 0 - 5
- 5 - 50
- 50 - 500
- 500 - 2592

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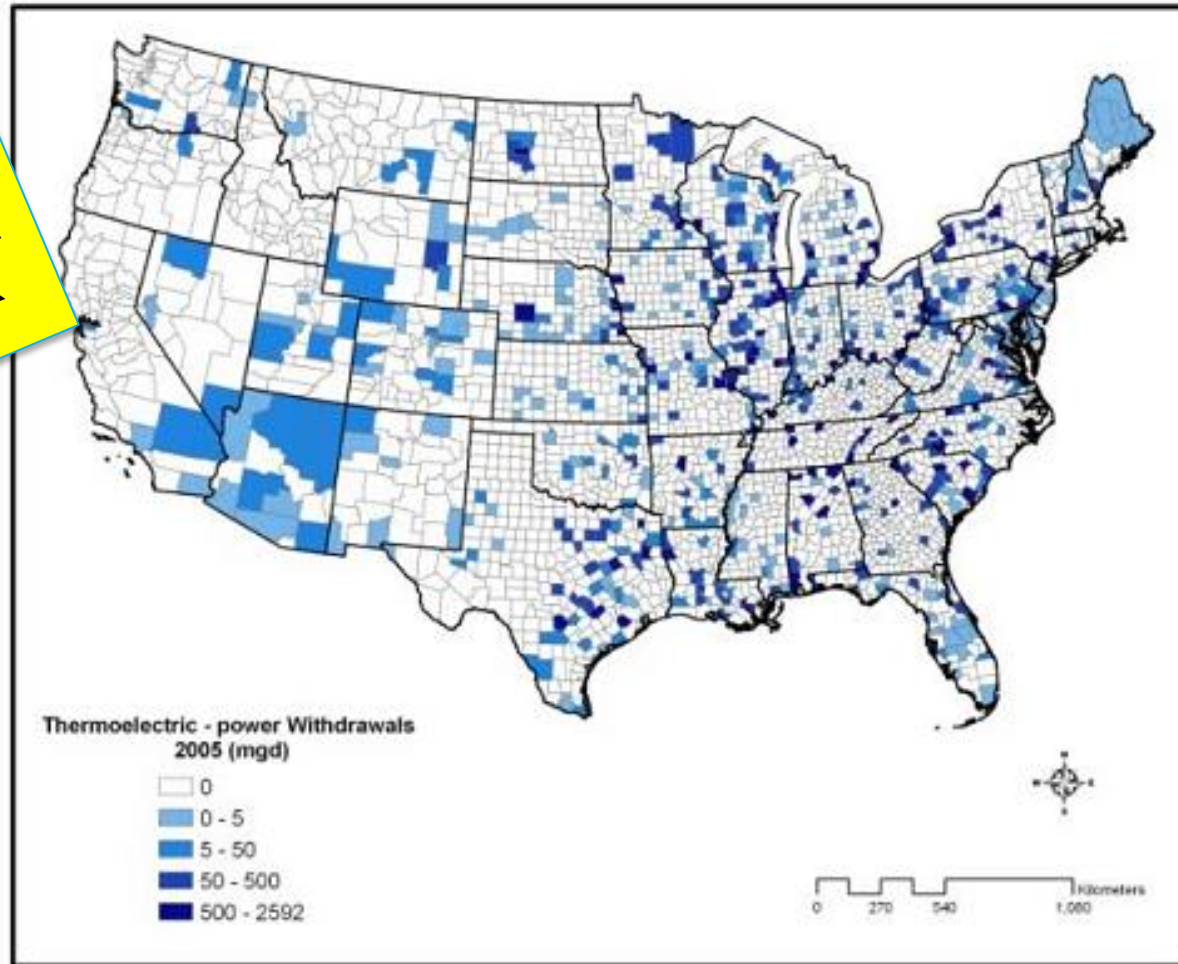
9c. EPRI – distribution of cooling technology
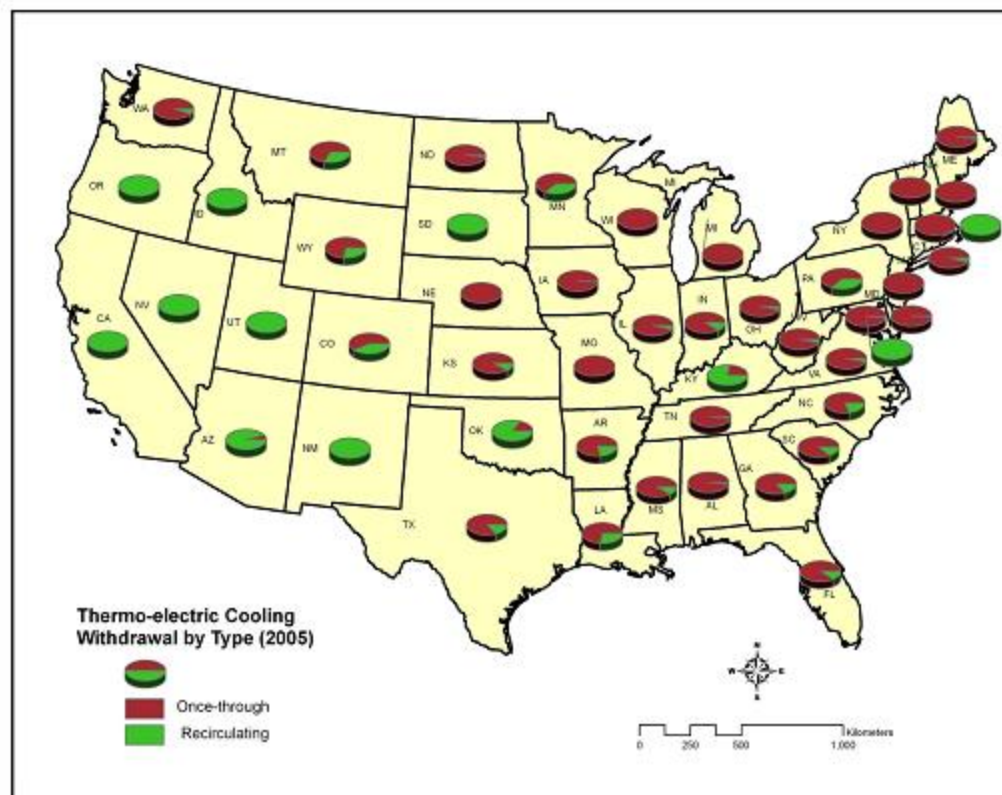
Figure 2-8
Thermoelectric cooling technology, proportion of freshwater once- through versus recirculating cooling in 2005 based on withdrawal, aggregated at the state level.

9d. USGS - Water withdrawals for thermoelectric power by state

Total withdrawals

EXPLANATION
Water withdrawals, in million gallons per day

- 0
- Greater than 0 to 2,000
- 2,000 to 4,000
- 4,000 to 6,000
- 6,000 to 9,000
- 9,000 to 13,500

West—east division for this report

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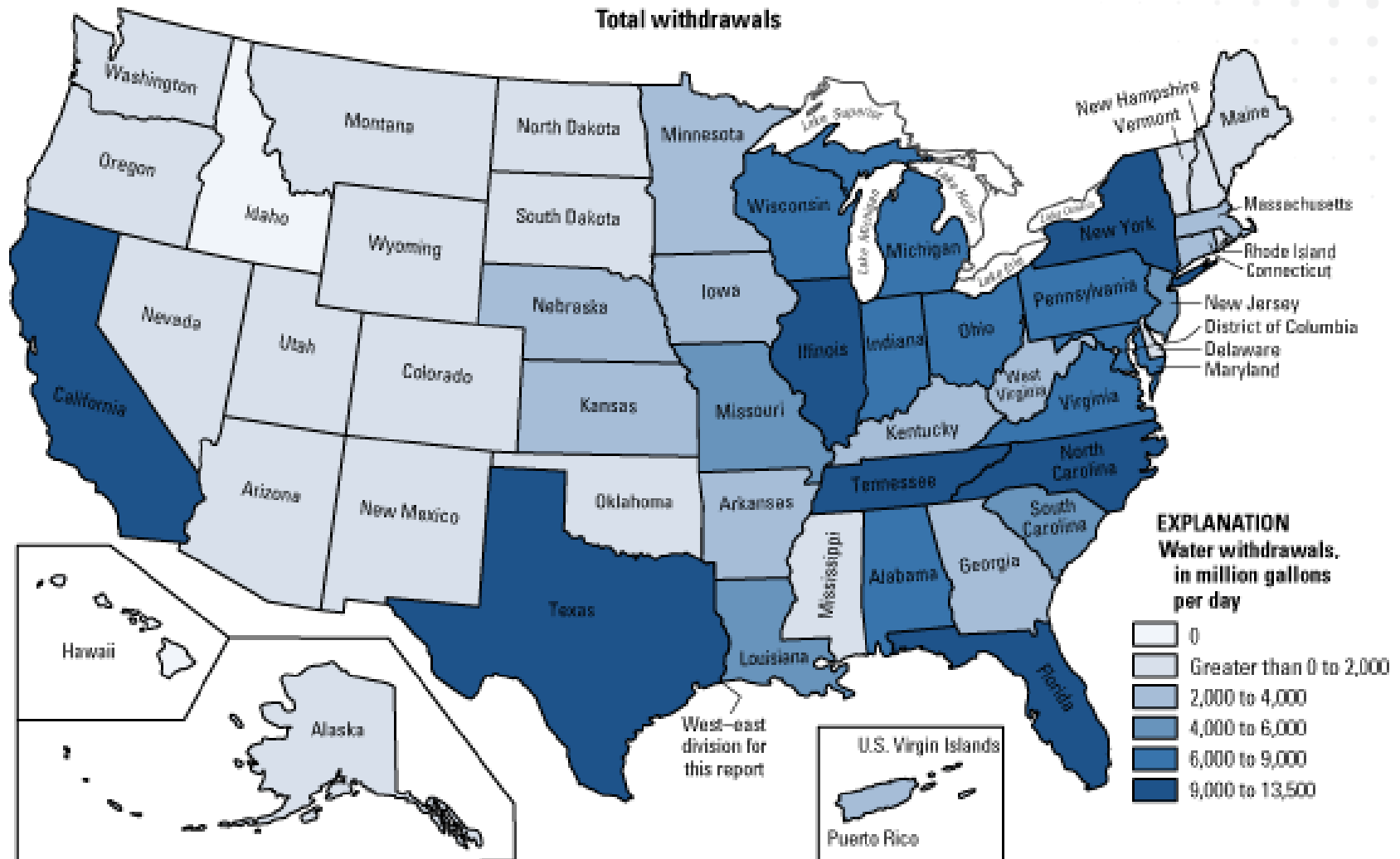
9e. USGS - Water withdrawals for thermoelectric power by state and water type

11. Another challenge relates to permitting issues due to water availability
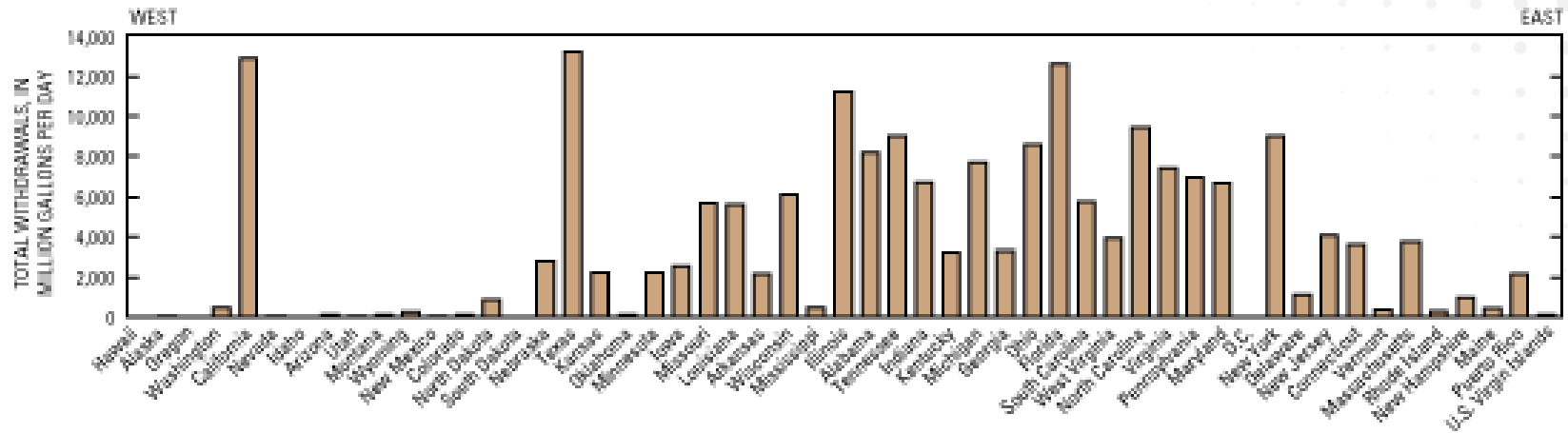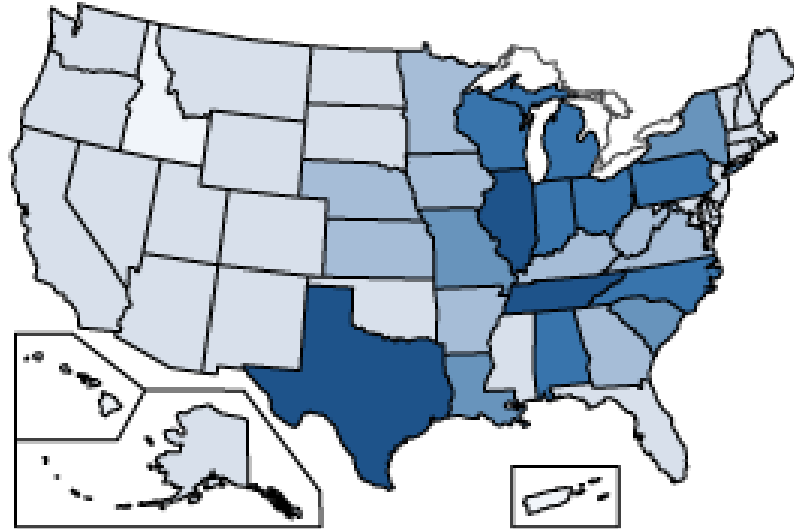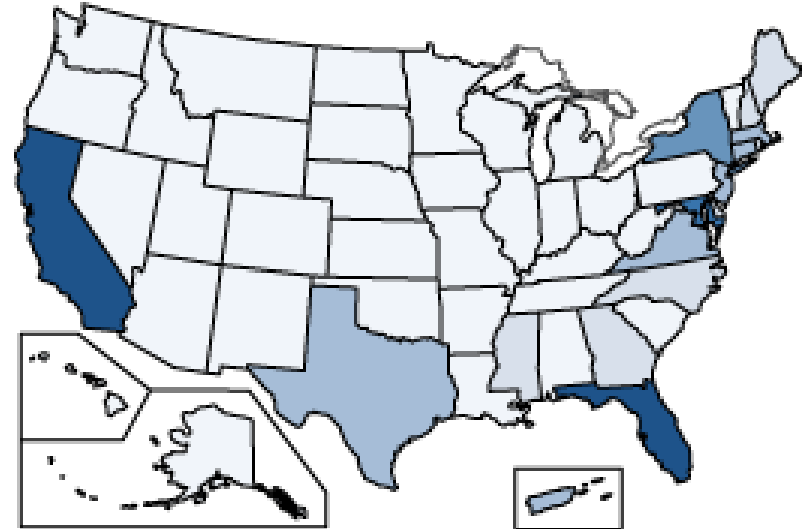
◆ Recent energy facility permitting
issues due to water availability

Working to understand these better

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13. Example of area (Colorado River Basin) where water use is approaching/exceeding supply
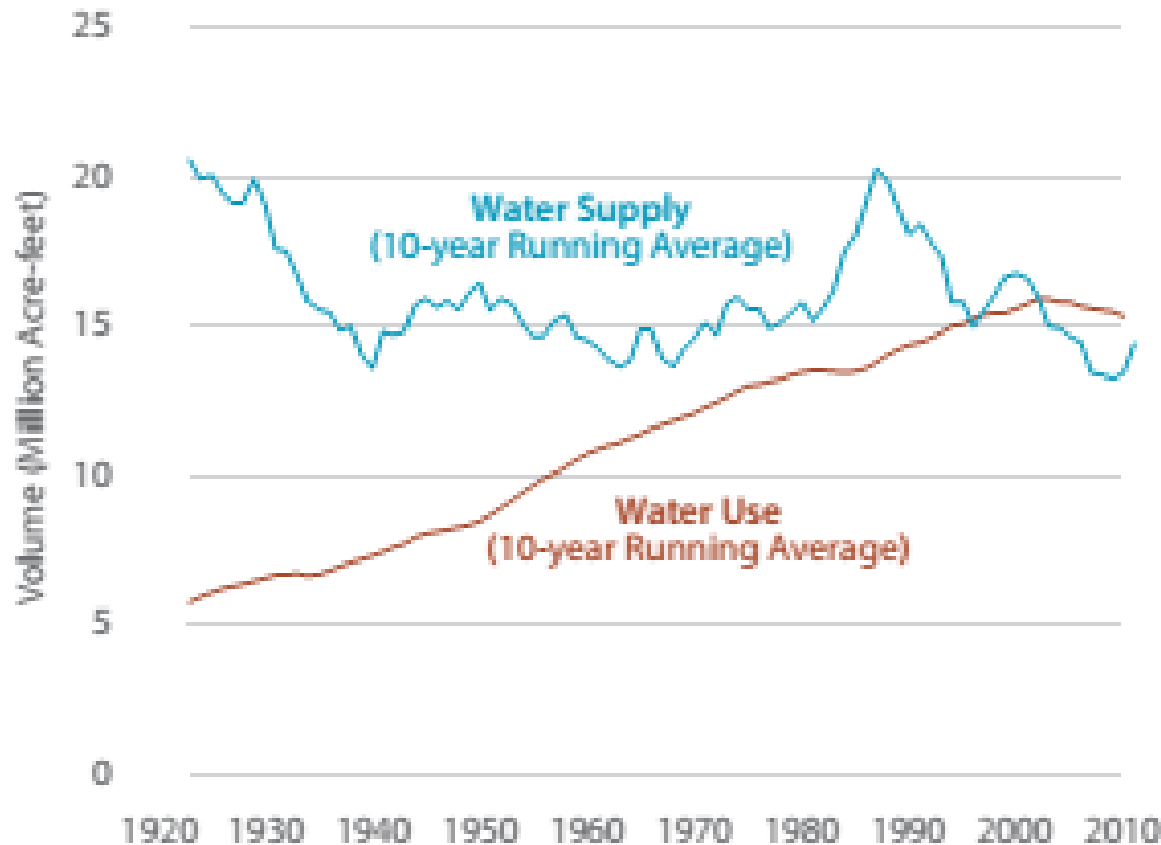
FIGURE 3. Water Supply versus Water Demand in the Colorado River Basin

Over the last century, the natural flow of the Colorado River has averaged roughly 16 million acre-feet (5 trillion gallons) per year. However, water use in the basin has risen over time, while water supply has been dropping because of drought. Rising demand for water has been met through drawdowns of water stored in reservoirs such as Lake Mead and Lake Powell.[12] Source: USBR 2012.

20. Changes in LCOE from retrofitting TE power plants to dry cooling/non-potable (lowest cost)

Total Cost $/MWh
- < $0.50
- $0.51 - $1.00
- $1.01 - $1.50
- $1.51 - $3.00
- $3.01 - $5.00
- $5.01 - $7.50
- $7.51 - $10.00
- $10.01 - $25.00
- $25.01 - $50.00
- $50.01 - $100.00
- $100.01 - $250.00
- > $250.00
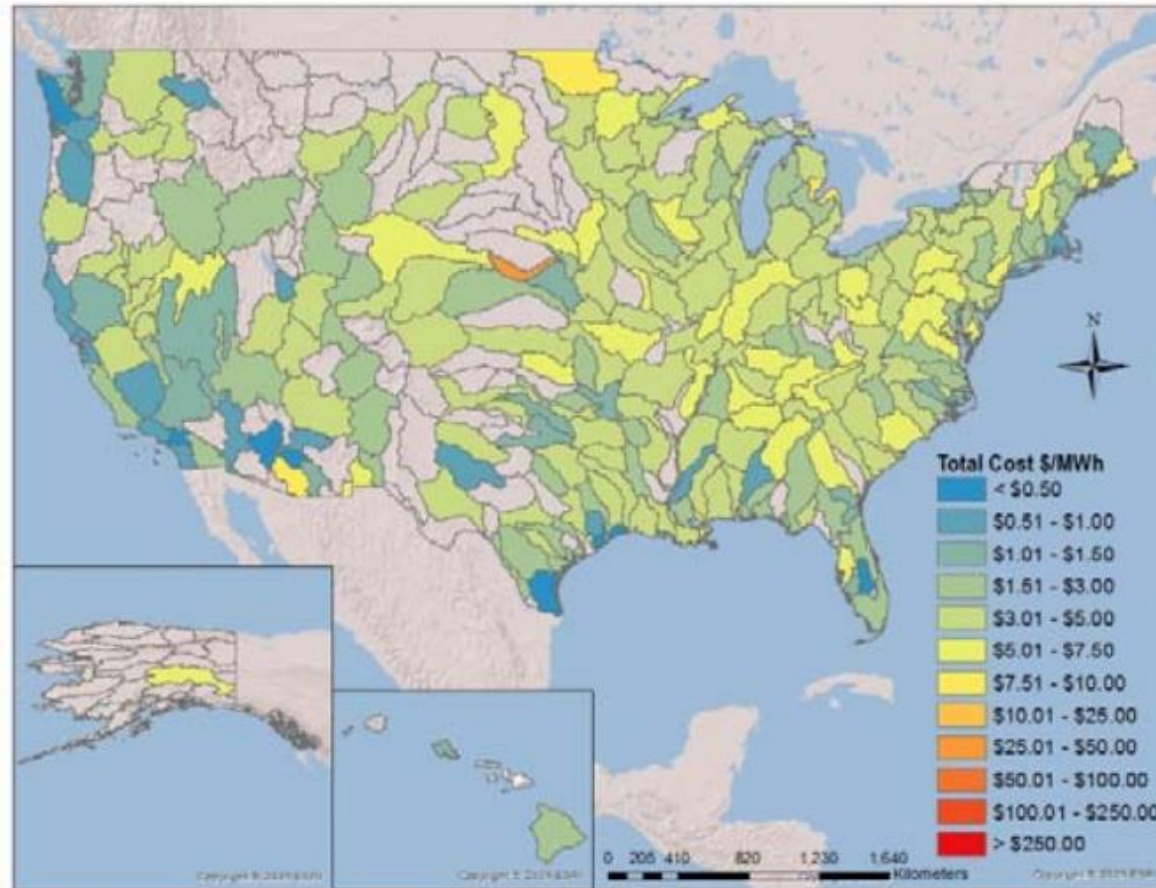
Next steps: Internal analysis to better understand this and integrate with future scenarios to assess vulnerability

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20. Costs of retrofits

	Capital Cost (Once-through to Recirculating) ($/kW)	Capital Cost (Once-through or Recirculating to Dry) ($/kW)	Capital Cost (Once-through to Recirculating) ($/kW)	Capital Cost (Once-through or Recirculating to Dry) ($/kW)	O&M cost (Once-through to Recirculating) ($/kW/yr.)	O&M cost (Once-through to Dry) ($/kW/yr.)	O&M cost (Recirculating to Dry) ($/kW/yr.)
	Average Difficulty Retrofits		Difficult Retrofits		All Retrofits		
Coal	90	220	140	330	2	5	3
Natural Gas Combined Cycle	40	170	65	270	2	10	8
Nuclear	90	220	140	330	2	5	3
Biopower/Biogas	90	220	140	330	2	5	3
Oil/Gas Simple Cycle	90	220	140	330	2	5	3
Geothermal	N/A	170	N/A	270	N/A	N/A	2
Concentrating Solar Power	N/A	170	N/A	270	N/A	N/A	2

Table 1. Capital and O&M costs, distinguished by fuel type, to retrofit a power plant from once-through to recirculating cooling, once-through to dry cooling, and recirculating to dry cooling. In the case of capital costs both average and difficult retrofit estimates are given. Data are from Woldeyesus et al. 2013.[42]

CHANGING WHAT'S POSSIBLE

Least cost retrofit distribution
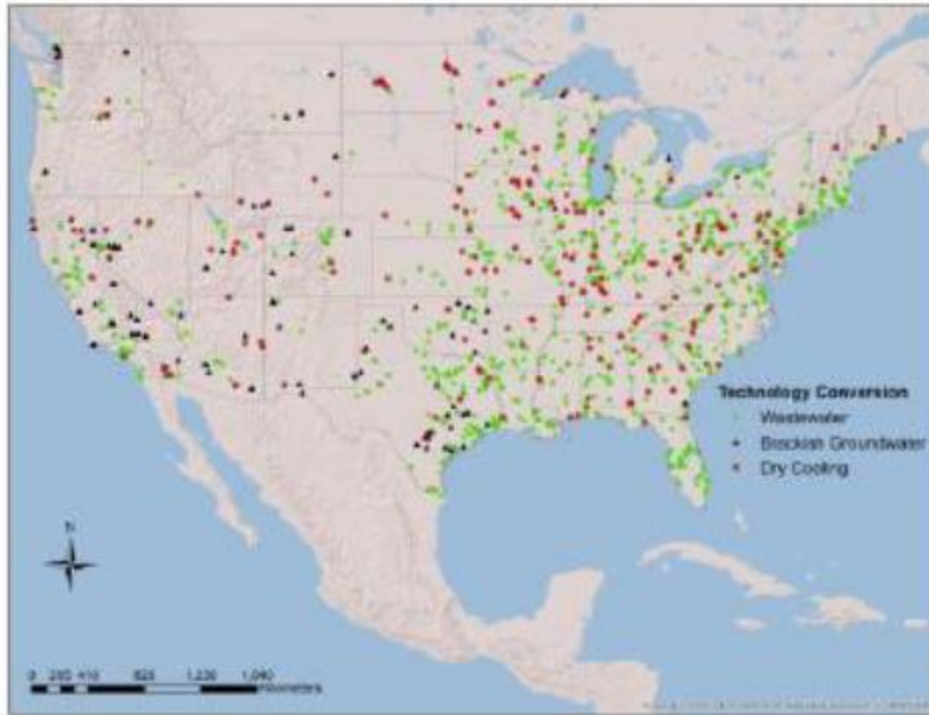
Evident in this map is that the brackish groundwater retrofits are largely limited to the Southwest, Texas, and Oklahoma. In contrast, wastewater and dry-cooling retrofits are relatively evenly distributed over the entire country. However, a little closer inspection reveals that many of the wastewater retrofits are co-located with metropolitan areas

In 180 of the 209 cases where dry cooling was the least cost alternative, dry cooling was the only option available to the plant (wastewater and brackish groundwater supply were insufficient in that location to meet power generation demands).

Total parasitic energy requirements are estimated at 140 million MWh, or roughly 4.5% of the total production from the retrofitted plants. Of this parasitic energy loss 118 million MWh are due to efficiency losses with dry cooling retrofits, 12 million MWh are the result of retrofits to recirculating cooling, and 10 million MWh are lost to pumping and treating water.

Least cost retrofit
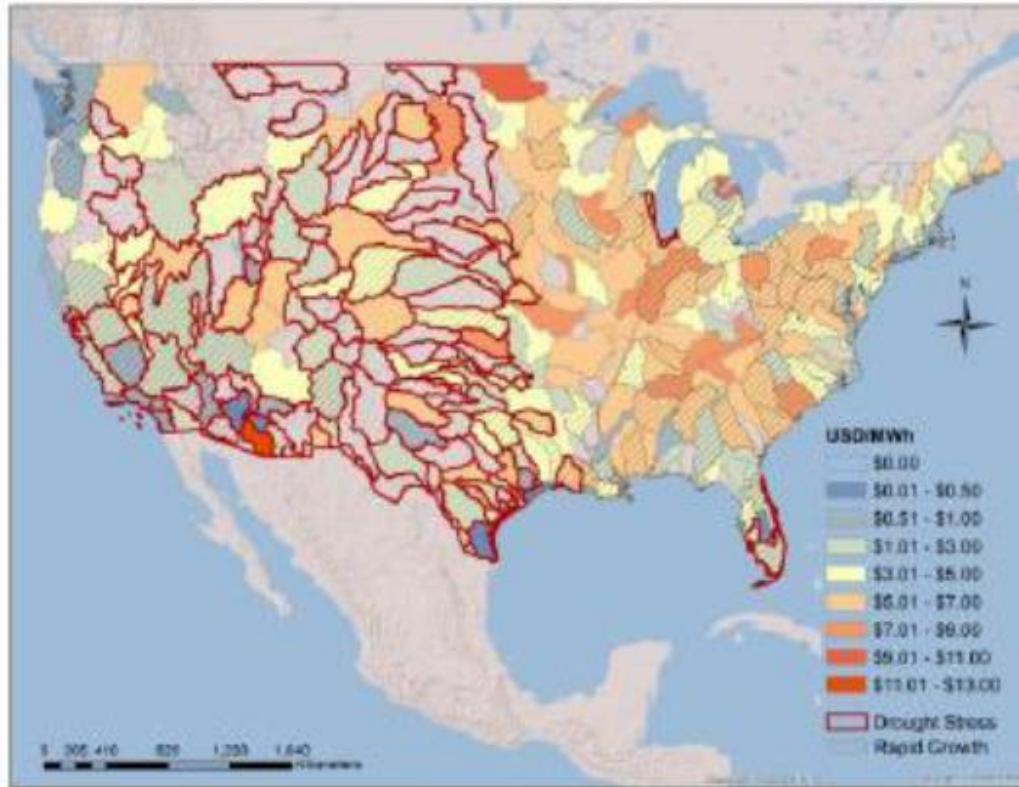
Figure 5. Least cost alternative ΔLCOE values associated with retrofitting to dry cooling or wet cooling using non-potable water aggregated and mapped at the 6-digit HUC level. Watersheds vulnerable to drought are outlined in red (watersheds mapped in red in Figure 2).

When considered on a plant level basis brackish groundwater is on average $1.35/MWh more expensive than a wastewater retrofit. In terms of capital costs, the wastewater retrofit is least expensive (average capital costs of $11.9 million), then brackish groundwater (average capital costs of $13.8 million), followed by a retrofit to dry cooling (average capital costs of $114.5 million). However, O&M costs for brackish water treatment are highest among the three options

EPA report on energy penalties

Cooling Type	Percent Maximum Load[a]	Nuclear Percent of Plant Output	Combined-Cycle Percent of Plant Output	Fossil-Fuel Percent of Plant Output
Wet Tower vs. Once-Through	67	1.7	0.4	1.7
Dry Tower vs. Once-Through	67	8.5	2.1	8.6
Dry Tower vs. Wet Tower	67	6.8	1.7	6.9

Table 3-1: National Average Annual Energy Penalty, Summary Table

[a] Average annual penalties occur at non-peak loads..

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EPA – Energy penalties

Table 3-3: Total Energy Penalties at 67 Percent Maximum Load[a]				
Location	Cooling Type	Nuclear Annual Average	Combined-Cycle Annual Average	Fossil-Fuel Annual Average
Boston	Wet Tower vs. Once-Through	1.6	0.4	1.6
	Dry Tower vs. Once-Through	7.4	1.8	7.1
	Dry Tower vs. Wet Tower	5.8	1.4	5.5
Jacksonville	Wet Tower vs. Once-Through	1.9	0.4	1.7
	Dry Tower vs. Once-Through	12.0	3.0	12.5
	Dry Tower vs. Wet Tower	10.1	2.5	10.8
Chicago	Wet Tower vs. Once-Through	1.8	0.4	1.8
	Dry Tower vs. Once-Through	7.8	1.9	7.7
	Dry Tower vs. Wet Tower	5.9	1.5	5.9
Seattle	Wet Tower vs. Once-Through	1.5	0.4	1.5
	Dry Tower vs. Once-Through	7.0	1.7	6.9
	Dry Tower vs. Wet Tower	5.5	1.3	5.4

[a] Average annual penalties occur at non-peak loads.

EPA - Energy penalties

Figure 1
Plot of Various Turbine Exhaust Pressure Correction Curves
for 100% and 67% Steam Loads
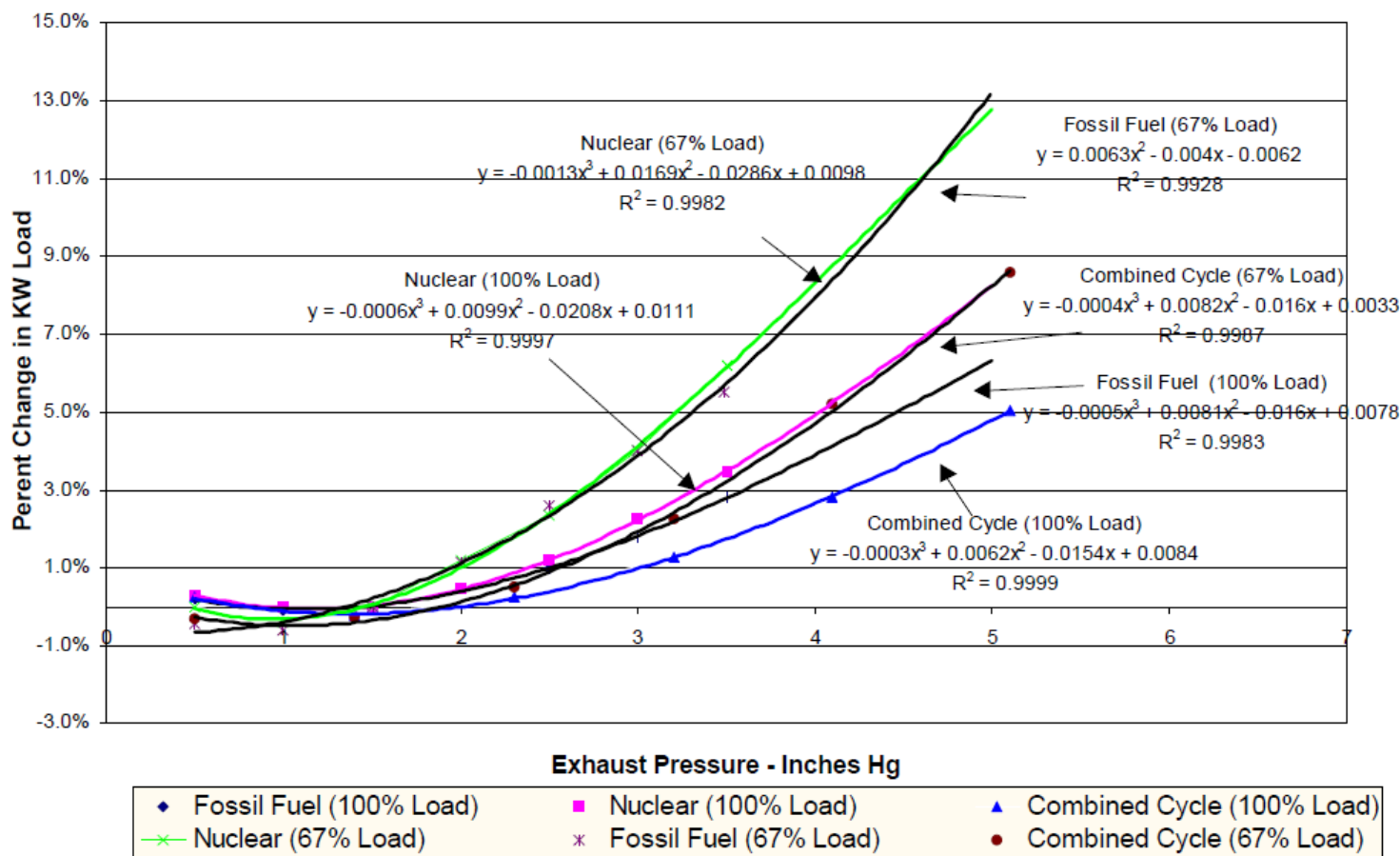
EPA – Energy penalties and temps

Table 3-11: Monthly Average Coastal Water Temperatures (°F)												
Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Boston, MA[a]	40	36	41	47	56	62	64.5	68	64.5	57	51	42
Jacksonville, FL[a]	57	56	61	69.5	75.5	80.5	83.5	83	82.5	75	67	60
Chicago, IL[b]	39	36	34	36	37	48	61	68	70	63	50	45
Seattle, WA[a]	47	46	46	48.5	50.5	53.5	55.5	56	55.5	53.5	51	49

[a] Source: NOAA Coastal Water Temperature Guides, (www.nodc.noaa.gov/dsdt/cwtg).

[b] Source: Estimate from multi-year plot "Great Lakes Average GLSEA Surface Water Temperature"

Table 3-13: Time-Weighted Averages for Eight-Hour Period from 8am to 4pm (°F)														
Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Design 1%
Boston	Wet Bulb	27.5	29.3	36.3	44.6	53.9	62.7	67.9	67.4	61.5	52.0	42.6	32.6	74.0
	Dry Bulb	33.0	35.3	43.2	53.5	63.8	73.9	80.0	78.2	70.4	59.9	49.5	38.4	88.0
Jacksonville	Wet Bulb	52.9	55.3	59.6	64.5	70.3	75.1	77.1	77.1	75.1	69.1	63.1	55.9	79.0
	Dry Bulb	59.8	63.6	70.3	76.6	83.0	87.2	89.3	88.1	85.1	77.8	70.6	62.6	93.0
Chicago	Wet Bulb	23.3	27.0	37.2	46.6	56.6	64.9	69.8	69.3	62.2	51.2	39.1	27.9	76.0
	Dry Bulb	27.6	31.8	43.9	55.7	67.9	77.4	82.5	80.6	72.4	59.9	45.0	32.2	89.0
Seattle	Wet Bulb	39.4	41.8	44.2	47.2	52.0	56.0	59.2	59.6	57.2	51.0	44.0	39.7	65.0
	Dry Bulb	44.3	47.8	51.5	55.6	61.8	67.2	71.6	71.6	67.3	58.1	49.0	44.3	82.0

EPA – Energy penalties

Location	Cooling Type	Percent Maximum Load	Nuclear Maximum Design	Nuclear Annual Average	Combined Cycle Maximum Design	Combined Cycle Annual Average	Fossil Fuel Maximum Design	Fossil Fuel Annual Average
Boston	Wet Tower vs. Once-through	67%	2.32%	0.73%	0.42%	0.14%	2.04%	0.88%
	Dry Tower vs. Once-through	67%	13.82%	4.96%	3.20%	0.98%	15.15%	4.69%
	Dry Tower vs. Wet Tower	67%	11.50%	4.23%	2.78%	0.84%	13.11%	3.81%
Jacksonville	Wet Tower vs. Once-through	67%	1.22%	1.03%	0.24%	0.18%	1.08%	0.93%
	Dry Tower vs. Once-through	67%	13.61%	9.63%	3.50%	2.14%	16.96%	10.06%
	Dry Tower vs. Wet Tower	67%	12.39%	8.60%	3.27%	1.96%	15.88%	9.14%
Chicago	Wet Tower vs. Once-through	67%	2.53%	0.98%	0.47%	0.16%	2.23%	1.02%
	Dry Tower vs. Once-through	67%	14.03%	5.39%	3.30%	1.07%	15.67%	5.30%
	Dry Tower vs. Wet Tower	67%	11.50%	4.41%	2.83%	0.91%	13.44%	4.27%
Seattle	Wet Tower vs. Once-through	67%	1.60%	0.67%	0.27%	0.11%	1.50%	0.74%
	Dry Tower vs. Once-through	67%	12.16%	4.60%	2.60%	0.90%	12.31%	4.50%
	Dry Tower vs. Wet Tower	67%	10.56%	3.93%	2.33%	0.79%	10.81%	3.75%
Average	Wet Tower vs. Once-through	67%	1.92%	0.85%	0.35%	0.15%	1.71%	0.89%
	Dry Tower vs. Once-through	67%	13.41%	6.14%	3.15%	1.27%	15.02%	6.14%
	Dry Tower vs. Wet Tower	67%	11.49%	5.29%	2.80%	1.12%	13.31%	5.24%

Note: See Section 3-1 for the total energy penalties. This table presents only the turbine component of the total energy penalty.

EPA – Cooling tower designs

Table AA-1. Cooling Tower Design Temperature, Range and Approach

STATE	YEAR	FLOW (GPM)	TEMPERATURE (DEG F)			RANGE (DEG F)	APPROACH (DEG F)	# OF CELLS
			HOT WATER	COLD WATER	WET BULB			
AL	2000	208000	85	72	62	13	10	10
OR	2000	152000	98	77.8	68.35	20.2	9.45	11
CA	2000	99746	94.3	72.5	55.5	21.8	17	8
NJ	2000	146000	90.3	75	52	15.3	23	10
AL	2000	278480	105	89	81	16	8	14
AL	2000	147361	112.5	96.7	84.7	15.8	12	7
IL	2000	189041	96.87	85.46	76	11.41	9.46	10
TX	2000	192300	104.3	87	79	17.3	8	12
TX	2000	106400	89.2	78.5	64.2	10.7	14.3	5
MO	1999	60000	85.3	67	52.4	18.3	14.6	4
FL	1999	21500	120	93	80	27	13	1
TX	1999	277190	105	89	81	16	8	14
CA	1999	101000	111.05	89	75	22.05	14	6
AL	1999	50000	107	86	80	21	6	4
MO	1999	25000	98	83	78	15	5	2
MS	1998	230846	106.2	91.2	84.7	15	6.5	12

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EPA – Air Cooled Condensors installed

Facility Name	City	State	Country	Size MW	Steam Flow lbs/hr	Turbine Exhaust Pressure In. Hg	Design Temp. °F	Year	Description	Sat. Steam Temp. °F	Temp. Difference °F
Neil Simpson I Sta.	Gillette	WY	USA	20	167,550	4.5	75	1968	Coal	130	55
NP Potter	Braintree	MA	USA	20	190,000	3.5	50	1975	Combine Cycle	120	70
Wyodak Sta.	Gillette	WY	USA	330	1,884,800	6	66	1977	Coal	141	75
Gerber Cogen	Gerber	CA	USA	3.7	52,030	2.03	48	1981	Combined Cycle Cogen	102	54
NAS North Is. Cogen	Coronado	CA	USA	4	65,000	5	70	1984	Combined Cycle Cogen	134	64
NTC Cogen	San Diego	CA	USA	2.6	40,000	5	70	1984	Combined Cycle Cogen	134	64
Chinese Sta.	China Camp	CA	USA	22.4	181,880	6	97	1984	Waste wood	141	44
Duchess Cnty. RRF	Poughkeepsie	NY	USA	7.5	50,340	4	79	1985	WTE	126	47
Sherman Sta.	Sherman Station	ME	USA	20	125,450	2	43	1985	Waste Wood	102	59
Olmstead Cnty. WTE	Rochester	MN	USA	1	42,000	5.5	80	1985	WTE	138	58
Chicago Northwest WTE	Chicago	IL	USA	1	42,000		90	1986	WTE		
SEMASS WTE	Rochester	MA	USA	54	407,500	3.5	59	1986	WTE	120	61
Haverhill RRF	Haverhill	MA	USA	46.9	351,830	5	85	1987	WTE	134	49
Cochrane Sta.	Cochrane	Ont.	CAN	10.5	90,000	3	60	1988	Combined Cycle Cogen	115	55
Grumman	Bethpage	NY	USA	13	105,700	5.4	59	1988	Combined Cycle Cogen	137	78
North Branch Power Sta.	North Branch	WV	USA	80	662,000	7	90	1989	Coal	147	57
Sayreville Cogen Pro.	Sayreville	NJ	USA	100	714,900	3	59	1989	Combined Cycle Cogen	115	56
Bellingham Cogen Pro.	Bellingham	MA	USA	100	714,900	3	59	1989	Combined Cycle Cogen	115	56
Spokane RRF	Spokane	WA	USA	26	153,950	2	47	1989	WTE	102	55
Exeter Energy L.P. Pro.	Sterling	CT	USA	30	196,000	2.9	75	1989	PAC System	114	39
Peel Energy from Waste	Brampton	Ont.	CAN	10	88,750	4.5	68	1990	WTE	130	62
Nipogen Power Plant	Nipogen	Ont.	CAN	15	169,000	3	59	1990	Combined Cycle Cogen	115	56
Linden Cogen Pro.	Linden	NJ	USA	285	1,911,000	2.44	54	1990	Combined Cycle Cogen	108	54
Maalaea Unit 15	Maui	HI	USA	20	158,250	6	95	1990	Combined Cycle	141	46

Table 4-1: Air Cooled Condenser Data for Systems installed by GEA Power Cooling Systems, Inc.

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EPRI – Energy penalties
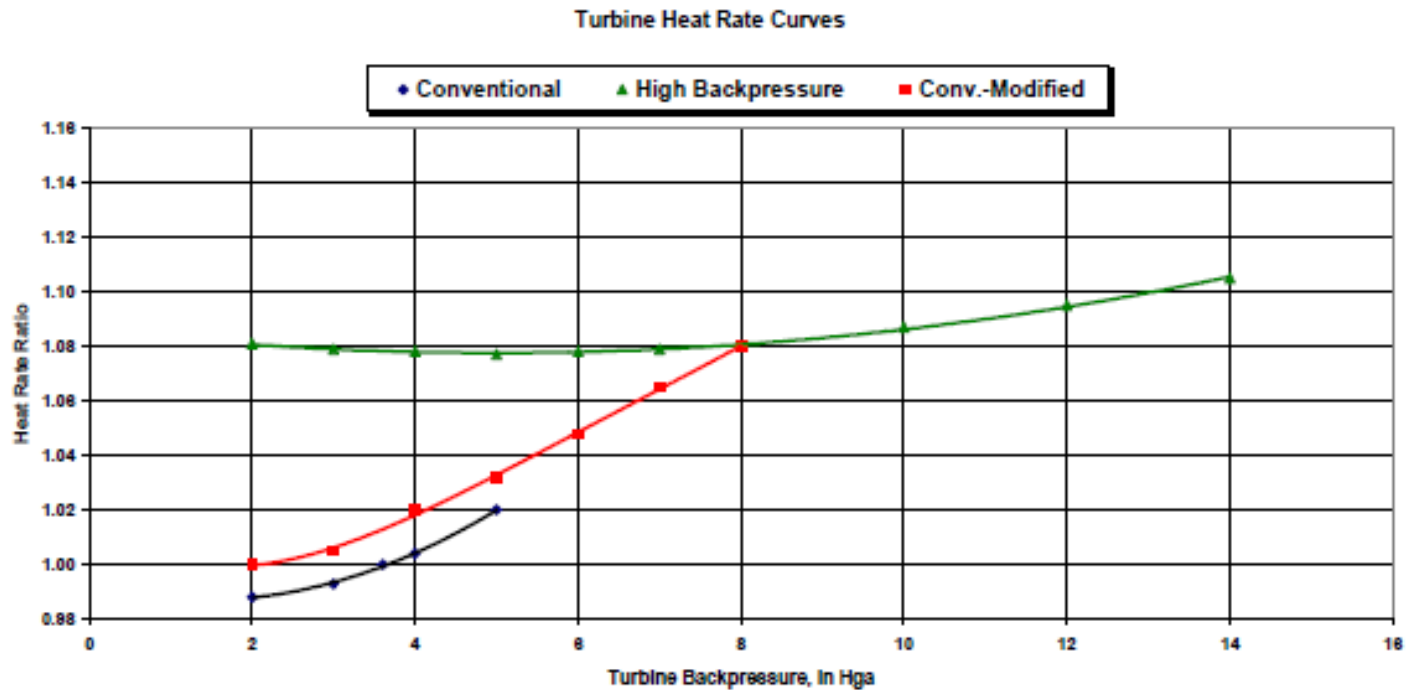
Figure 2-4
Comparison of Heat Rate Characteristics (for conventional vs. extended backpressure operation.)

EPRI – Energy penalties

Table 2-1
Base Plant Characteristics for Combined-Cycle Plants

Quantity	Value
Nominal plant capacity, MW	500
Configuration	2 x 1
Gas turbine output, MW	330 (2 x 165 MW per turbine)
Steam turbine output, MW	170
Steam turbine exhaust flow, lb/hr	1.1×10^6 pounds per hour @ 5% moisture
Turbine back pressure, in Hga	2.5 in Hga; (T_{cond} = 108.7 °F)
Cooling system heat load, Btu/hr	985. x 10^6 Btu/hr
Steam turbine heat rate, Btu/kWh	9,200 (at 2.5 in Hga)
Heat rate correction curve	See Figure 2.4
Max. Allowable Backpressure, in Hga	
- with wet cooling	5.0
- with dry cooling	8.0

EPRI – steam condenser specs and costs

Table 3-1
Steam Condenser Budget Price Summary

Steam Flow	Cold Water Inlet Temperature	Range	Terminal Temperature Difference	Cooling Water Flow	Tube Size	Tube Side Pressure Drop	Surface Area	Budget Price	Price per Area
MMlb/hr	F	F	F	gpm	in. OD x BWG	ft. H2O	Sq. ft.	$	$/sq. ft.
1.1	70	20	18.7	112,000	1.25 x 22 BWG	15.3	76,905	$800,000	$10.40
	75	20	13.7	112,000	1.125 x 22 BWG	17.7	93,035	$872,000	$9.37
	80	20	8.7	112,000	1.00 x 22 BWG	21.9	119,127	$1,014,000	$8.51
	85	15	8.7	149,333	1.125 x 22 BWG	18.9	133,220	$1,082,000	$8.12
	90	10	8.7	224,000	1.25 x 22 BWG	14.9	150,890	$1,217,000	$8.07
2.5	70	20	18.7	245,000	1.25 x 22 BWG	16.1	168,260	$1,295,000	$7.70
	75	20	13.7	245,000	1.25 x 22 BWG	16.3	203,200	$1,419,000	$6.98
	80	20	8.7	245,000	1.125 x 22 BWG	22.5	264,555	$1,705,000	$6.44
	85	15	8.7	326,700	1.25 x 22 BWG	18.3	292,180	$1,817,000	$6.22
	90	10	8.7	490,000	1.25 x 22 BWG	15	329,145	$2,158,000	$6.56

EPRI dry cooling sites and estimates

Table 3-8
Specific ACC Design Points

	Case Study Descriptions				
	1	**2**	**3**	**4**	**5**
Climate Type	Arid, hot	Humid, hot	Arid, extreme	Moderate, cool	Moderate, warm
Met Data based on	El Paso, TX	Jacksonville, FL	Bismarck, ND	Portland, OR	Pittsburgh, PA
Design Steam Flow, lb/hr	1,100,000	1,100,000	1,100,000	1,100,000	1,100,000
Design Backpressure, in Hga	2.5	2.5	2.5	2.5	2.5
Site Elevation, ft	10	10	10	10	10
Turbine Exhaust Moisture, %	5	5	5	5	5
Design Ambient, F	80	79	65	65	69
Design ITD, F	28.7	29.7	43.7	43.7	39.7

Table 3-9
Vendor-Supplied Estimates of Equipment Cost and Power Requirements

	Vendor A*		Vendor B		Vendor C	
	Equipment Cost MM$	Fan Power (at design) HP	Equipment Cost MM$	Fan Power (at design) HP	Equipment Cost MM$	Fan Power (at design) HP
Site 1	23.2	9,719	24.0	7,180	19.6	7,300
Site 2	22.3	9,234	24.0	7,180	19.6	6,187
Site 3	14.2	5,988	16.0	4,110	13.9	4,553
Site 4	14.2	5,988	16.0	4,110	13.9	4,553
Site 5	15.9	6,428	18.0	3,930	14.9	4,880

* Vendor A based on 32 ft. diameter fans; B and C on 34 ft. fans

EPRI – Dry cooling costs

Table 3-12
Summary of total dry cooled system cost estimates

Vendor	Case	Design Information			Cost Estimates					
		Design ITD F	No. of Cells n	Fan Power HP	Equipment MM$	Erection MM$	Electrical MM$	Steam Duct MM$	Aux. Cooling MM$	Total MM$
A	1	28.8	55	9,719	23.2	9.9	1.65	0.15	2.6	37.5
(32 ft. fan)	2	29.8	55	9,234	22.3	9.5	1.65	0.15	2.5	36.1
	3	43.8	35	5,988	14.2	6.1	1.05	0.15	1.6	23.1
	4	43.8	35	5,988	14.2	6.1	1.05	0.15	1.6	23.1
	5	39.8	35	6,428	15.9	6.8	1.05	0.15	1.8	25.7
B	1	28.8	40	7,180	24.0	10.3	1.2	0.15	2.7	38.3
(34 ft. fan)	2	29.8	40	7,180	24.0	10.3	1.2	0.15	2.7	38.3
	3	43.8	24	4,110	16.0	6.9	0.72	0.15	1.8	25.5
	4	43.8	24	4,110	16.0	6.9	0.72	0.15	1.8	25.5
	5	39.8	30	3,930	18.0	7.7	0.9	0.15	2.0	28.8
C	1	28.8	40	7,339	19.6	9.6	1.2	0.15	2.3	32.8
(34 ft. fan)	2	29.8	40	6,220	19.6	9.6	1.2	0.15	2.3	32.8
	3	43.8	28	4,578	13.9	6.9	0.84	0.15	1.6	23.4
	4	43.8	28	4,578	13.9	6.9	0.84	0.15	1.6	23.4
	5	39.8	30	4,906	14.9	7.3	0.9	0.15	1.7	25.0
A	1	28.8	50	8,747	23.8	10.2	1.5	0.15	2.7	38.4
(adjusted to	2	29.8	50	8,311	22.9	9.8	1.5	0.15	2.6	37.0
34 ft. fan)	3	43.8	35	5,389	14.6	6.3	1.05	0.15	1.6	23.7
	4	43.8	35	5,389	14.6	6.3	1.05	0.15	1.6	23.7
	5	39.8	35	5,785	16.4	7.0	1.05	0.15	1.8	26.4

CHANGING WHAT'S POSSIBLE

EPRI – range of cost of water

Table 4-11
Summary of Water Costs

Costs	Minimum $/1,000 gallons	Low $/1,000 gallons	Medium $/1,000 gallons	High $/1,000 gallons
Acquisition (1)	Nil	$0.50	$1.25	$3.00
Delivery (2)	Nil	$0.13	$0.57	$1.20
Treatment/Disposal (3)	$0.10	$0.22	$1.00	$4.28
Total	**$0.10**	**$0.85**	**$2.82**	**$8.48**

(1) from Table 4-5
(2) from Table 4-7
(3) from Table 4-11

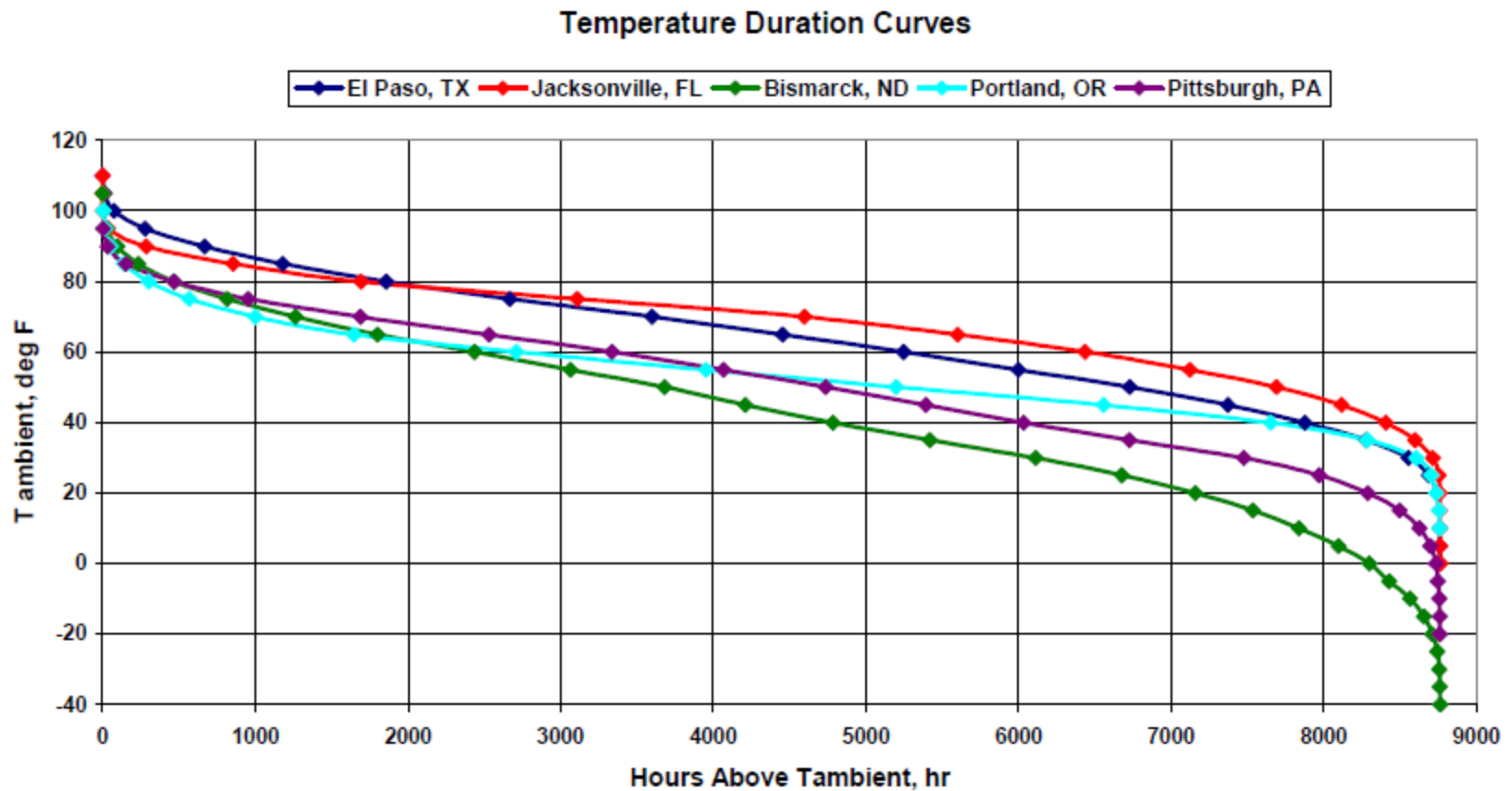# EPRI – site temps and characteristics

Figure 5-1
Case Study Site Temperature Duration Curves

EPRI – performance of ACC at site 1

Table 7-1

Illustrative Performance for ACC at Site 1; Combined-Cycle Plant

| Site Temperature Characteristics				Performance of ACC (Design ITD = 41.1 F)							
Thigh	Tlow	Tav	Hours in Range	Tcond	Backpressure	Gross Plant Output	Lost Output	Fan Power	Fan Energy	Net Plant Output	Energy Generated
F	F	F	hr	F	in Hga	MW	MWh	kW	kWh	MW	MWh
114	110	112	1	148.92	7.37	147	23	4,154	4,000	143	143
109	105	107	12	144.55	6.61	150	240	4,192	50,000	146	1,750
104	100	102	61	140.18	5.91	153	1,013	4,230	258,000	149	9,099
99	95	97	207	135.81	5.28	157	2,727	4,267	883,000	153	31,580
94	90	92	387	131.44	4.70	160	3,852	4,305	1,666,000	156	60,272
89	85	87	510	127.07	4.18	163	3,630	4,343	2,215,000	159	80,855
84	80	82	682	122.70	3.71	165	3,228	4,380	2,987,000	161	109,725
79	75	77	806	118.33	3.29	167	2,265	4,418	3,561,000	163	131,194
74	70	72	934	113.96	2.91	169	1,240	4,455	4,161,000	164	153,379
69	65	67	856	109.59	2.56	170	205	4,493	3,846,000	165	141,469
64	60	62	791	105.22	2.26	171	-401	4,531	3,584,000	166	131,287
59	55	57	751	100.85	2.00	171	-711	4,568	3,431,000	166	124,950
54	50	52	732	96.48	2.00	171	-693	4,376	3,203,000	167	121,930
49	45	47	642	92.11	2.00	171	-608	3,835	2,462,000	167	107,285
44	40	42	505	87.74	2.00	171	-478	3,416	1,725,000	168	84,603
39	35	37	401	83.37	2.00	171	-379	3,094	1,241,000	168	67,309
34	30	32	277	79.00	2.00	171	-262	2,849	789,000	168	46,563
29	25	27	133	74.63	2.00	171	-126	2,660	354,000	168	22,382
24	20	22	51	70.26	2.00	171	-48	2,513	128,000	168	8,590
19	15	17	16	65.89	2.00	171	-15	2,392	38,000	169	2,697
14	10	12	3	61.52	2.00	171	-3	2,287	7,000	169	506
9	5	7	1	57.15	2.00	171	-1	2,187	2,000	169	169
4	0	2	0	52.78	2.00	171	0	2,088	0	169	0

EPRI – costs for ACC at site 1
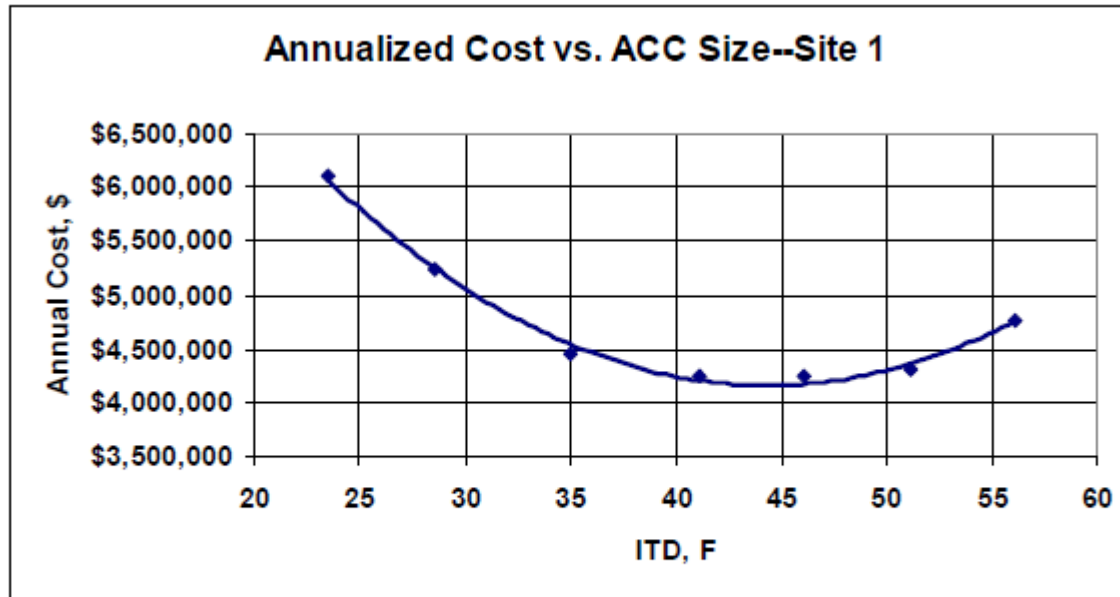
Figure 7-1
Annualized Cost vs. ITD---Site 1; Combined-Cycle Plant

EPRI – optimized wet cooled at each of the 5 sites

Table 7-6
Optimized Wet Systems at Five Sites; Combined-Cycle

Optimized Wet Systems at Five Sites					
	Site 1	Site 2	Site 3	Site 4	Site 5
Approach, F	12.5	7.5	12.5	12.5	12.5
Range, F	22.5	15	20	22.5	17.5
Flow, gpm	97,000	146,000	110,000	97,000	125,000
CWT, F	81.5	86.5	83.5	80.5	85.5
HWT, F	104	101.5	103.5	103	103
TTD, F	4.5	7.0	5.0	5.5	5.5
LMTD, F	12.5	13.0	12.4	13.8	12.2
Cond Cost	$1,330,000	$1,349,000	$1,351,000	$1,260,000	$1,377,000
Tower Cost	$4,445,000	$5,103,000	$4,445,000	$4,445,000	$4,445,000
System Cost	$5,775,000	$6,452,000	$5,796,000	$5,705,000	$5,822,000
Fan Power, HP	928	1,164	928	928	928
Pumping Power, HP	1,106	1,665	1,254	1,106	1,425
Power Cost	$465,000	$647,000	$499,000	$465,000	$538,000
Annualized Cost	$927,000	$1,163,000	$963,000	$922,000	$1,004,000

EPRI – ACC is currently 3.5X to 4.5X the cost of wet cooled across range of environments
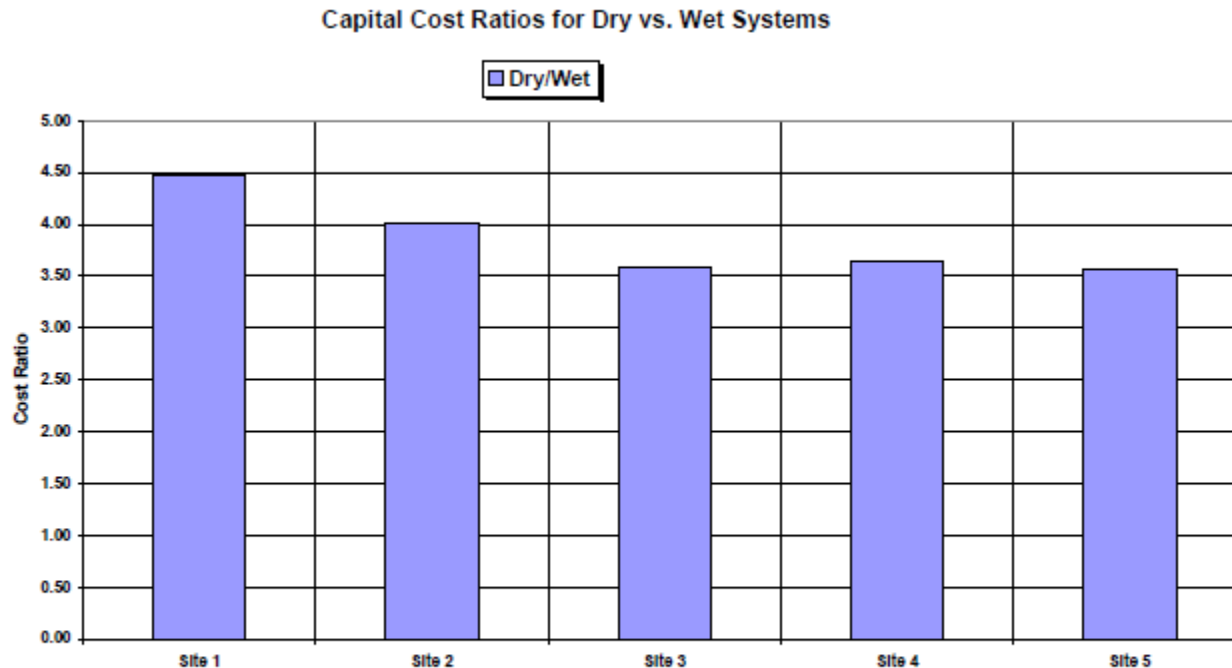

Figure 7-5
Capital Cost Ratios for Optimized Wet and Dry Systems for Each Site

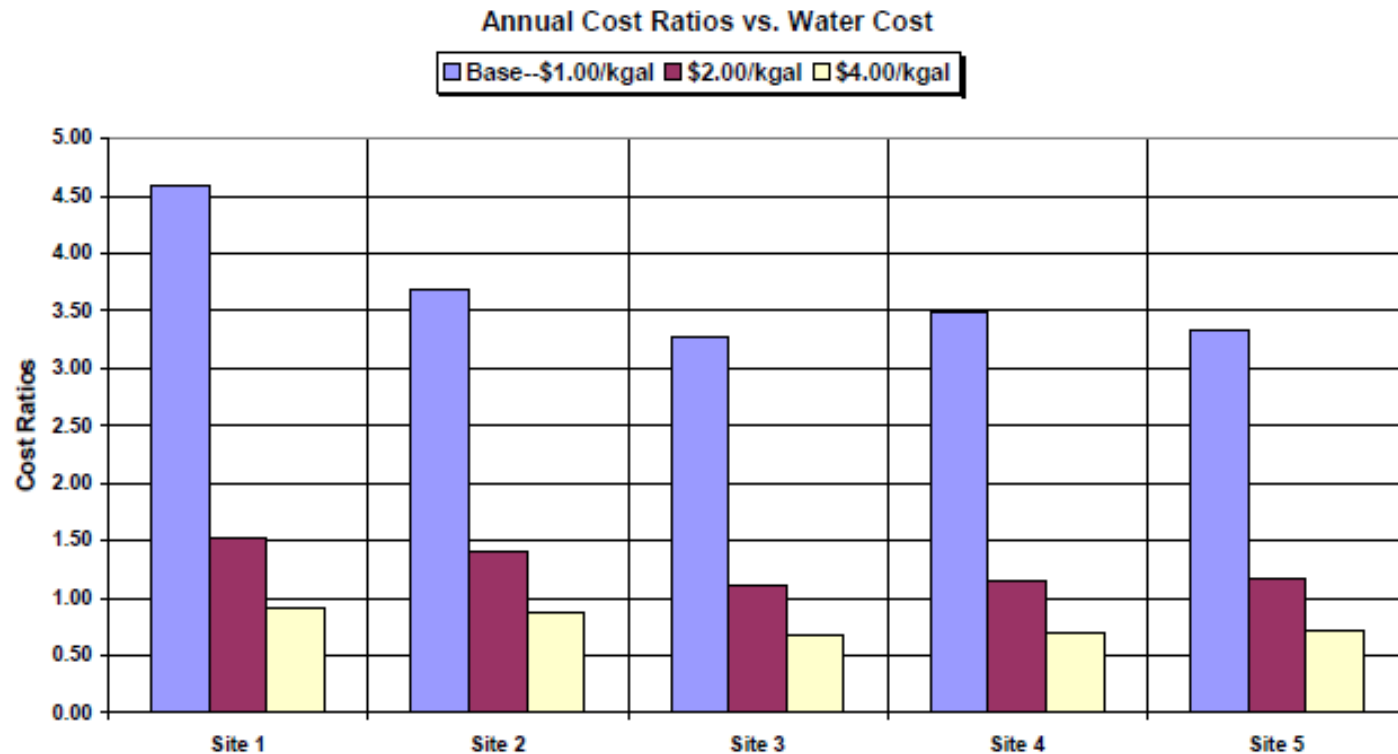# EPRI – breakeven cost of water somewhere around $2 to $3/kgal

Figure 7-8
Effect of Cost of Water on Annual Cost Ratios

Hightower presentation

Dry and Hybrid Cooling Issues and Opportunities

- 90% Less water consumption

- 6 % loss in production

- 20% reduced capacity at hottest hours

- 10% increase in capital cost
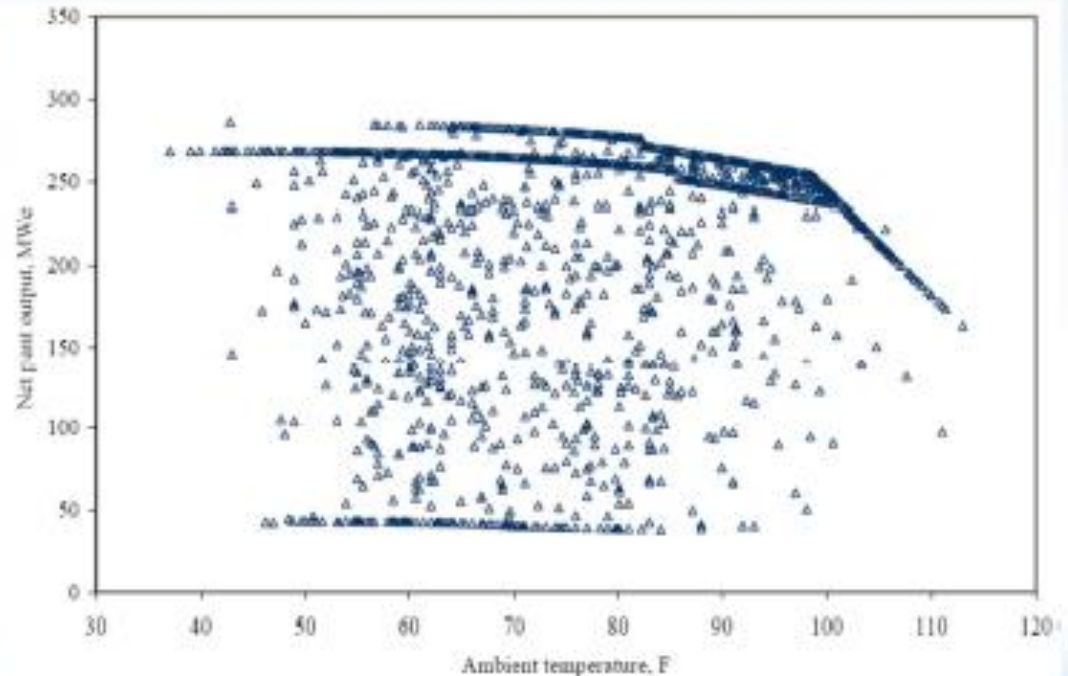
- 1-2 ¢ /kWh increase in cost of power

Figure 5 Net Plant Output as a Function of Ambient Temperature, Dry Heat Rejection

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DOE/Argonne – location information

Table 2 - Locations for Model Runs

Site Name	Location	Water Body	1% Highest Dry Bulb Temp (°F)	1% Highest Wet Bulb Temp (°F)	Humidity (lbs H_2O/lb dry air)	Summer Surface Water Temp. (°F)
Delaware River Basin	Philadelphia, PA	Delaware River	93	79	0.01849	76
Michigan/Great Lakes	Detroit, MI	Lake Erie	92	76	0.01597	73
Ohio River Valley	Indianapolis, IN	White River	94	78	0.01733	76
South	Atlanta, GA	Chattahoochee River	95	78	0.01712	79
Southwest	Yuma, AZ	Colorado River	111	79	0.01469	82

DOE/Argonne – location information

Table 3 – Monthly Average Temperatures

Site Name	Temperatures (° F)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Delaware River Basin	Wet Bulb	30.3	32.1	38.3	46.9	56.8	65.3	70.0	68.5	62.3	52.3	42.6	33.8
	Dry Bulb	30.3	33.0	42.4	52.3	62.9	71.7	76.7	75.6	68.2	56.4	46.4	35.6
	Surface Water	36.9	34.6	47.3	53.8	63.0	73.9	80.6	80.6	71.2	65.1	53.4	48.0
Michigan/Great Lakes	Wet Bulb	23.7	26.0	32.7	42.5	53.1	61.9	66.1	65.1	57.8	47.3	37.0	27.9
	Dry Bulb	24.6	26.7	36.5	48.2	59.8	69.3	74.1	72.4	65.1	53.5	41.9	29.8
	Surface Water	37.3	35.9	34.5	39.6	51.2	63.9	72.0	73.0	69.1	59.9	51.7	43.9
Ohio River Valley	Wet Bulb	26.5	30.3	37.4	46.6	56.7	65.2	68.8	67.3	60.2	49.7	39.4	27.7
	Dry Bulb	25.5	29.6	41.3	52.4	62.6	71.8	75.3	73.1	66.6	54.6	43.0	30.9
	Surface Water	46.3	45.6	54.1	57.7	68.0	73.3	77.1	76.9	71.3	62.5	51.7	37.3
South	Wet Bulb	39.1	42.4	47.6	53.8	62.5	69.0	72.1	71.2	66.0	53.3	48.4	38.5
	Dry Bulb	41.0	44.9	53.3	61.4	69.1	76.0	78.7	78.0	72.6	62.3	53.1	44.5
	Surface Water	54.0	55.8	57.7	68.2	73.2	75.0	81.7	83.5	75.0	69.4	63.7	58.8
Southwest	Wet Bulb	43.9	46.1	48.5	52.2	56.6	62.0	70.0	70.5	65.7	57.4	48.9	44.0
	Dry Bulb	56.4	60.6	64.8	71.2	78.8	87.6	93.6	92.6	86.7	76.1	64.1	56.4
	Surface Water	51.6	55.6	59.4	65.5	70.7	75.6	77.7	78.4	76.5	70.7	61.5	53.8

DOE/Argonne estimate of energy penalty

Table 6 – Estimated Annual Energy Penalty

Site Location	Energy Penalty Relative to Once-Through Cooling System (%)			Energy Penalty Relative to Wet Tower (%)	
	Wet Tower	Indirect Dry Tower - 20 °F Approach	Indirect Dry Tower - 40 °F Approach	Indirect Dry Tower - 20 °F Approach	Indirect Dry Tower - 40 °F Approach
Delaware River Basin	1.18 (3.12)	4.71 (9.27)	8.23 (13.23)	3.57	7.13
Michigan/Great Lakes	1.47 (3.08)	4.17 (9.75)	8.05 (13.21)	3.29	6.68
Ohio River Valley	1.14 (2.98)	4.50 (9.61)	7.91 (13.42)	3.39	6.84
South	0.82 (2.41)	5.20 (9.33)	8.82 (13.14)	4.41	8.07
Southwest	0.80 (2.06)	7.70 (12.04)	11.37 (15.79)	6.96	10.66

( )- Peak energy penalty model results run using a 15 degree F range.

Burns and Michelelli – cooling trends
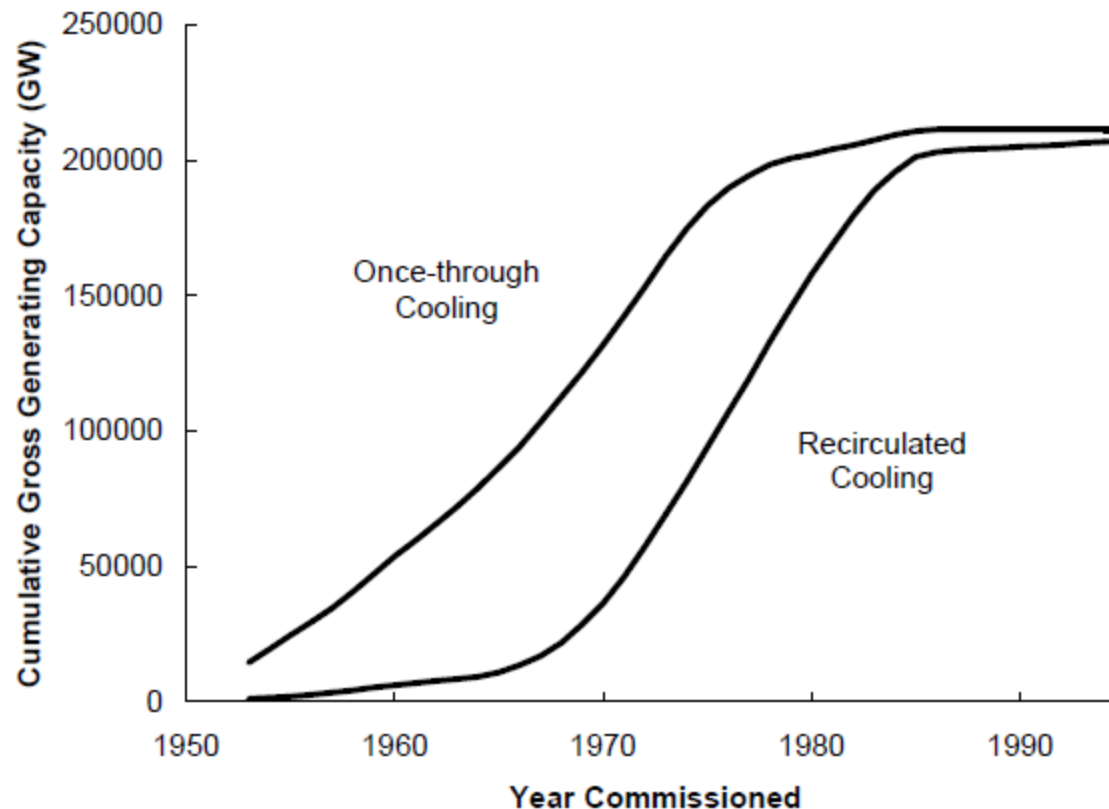
Figure 1
Growth of Once-through and Recirculated Cooling[1]

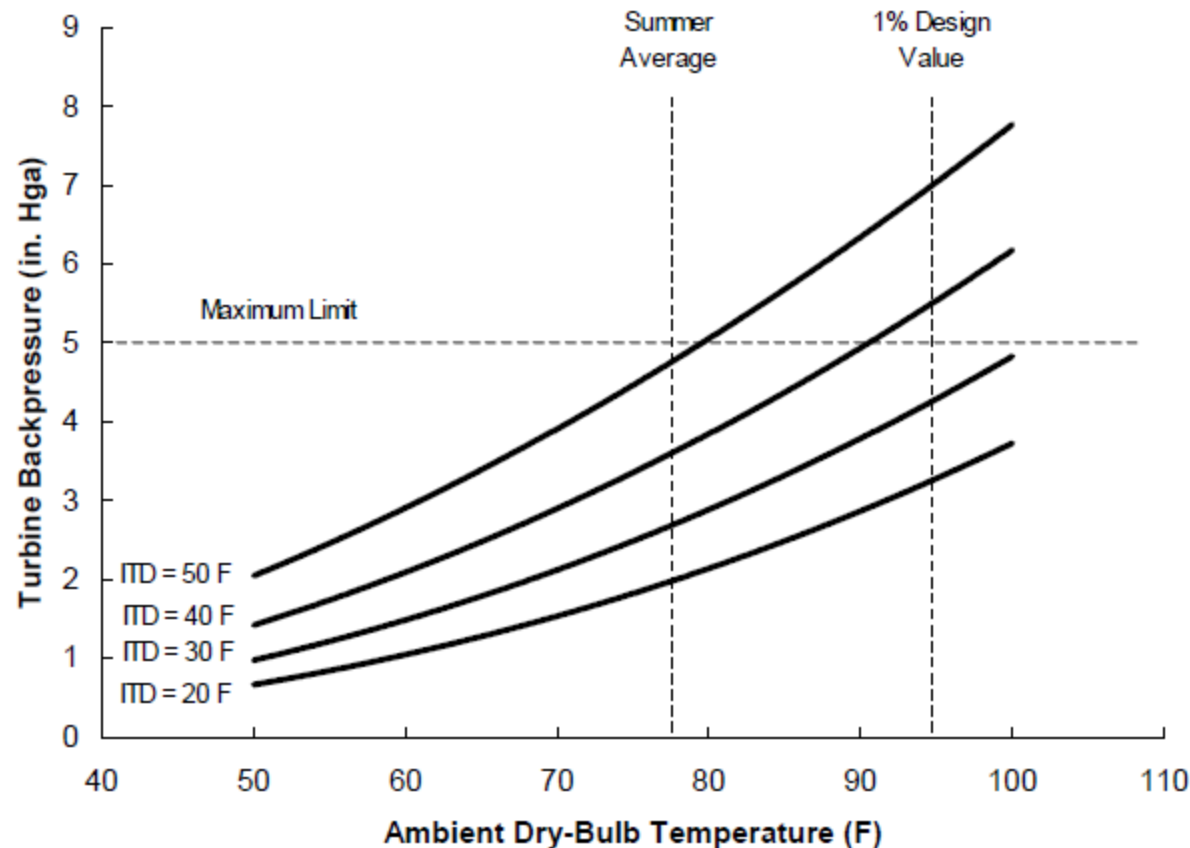# Burns and Micheletti – dry bulb to backpressure relationship

Figure 2
Ambient Dry-Bulb Temperature vs Turbine Backpressure

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Dry cooling economic benefits and challenges

Benefits	Challenges
Flexibility in location – could be put closer to end use/customer	Lower efficiency
Saves water	Upper temp limited by backpressure limits of turbines (perhaps turbine redesign)
Plume abatement	Fans and other parasitics
Avoids water regs	Greater footprint (but, higher surface area to volume ratio?)
	Ambient temp has higher variability

The US total water withdrawal was 400BG/d; total freshwater withdrawal was 330BG/d (2000)
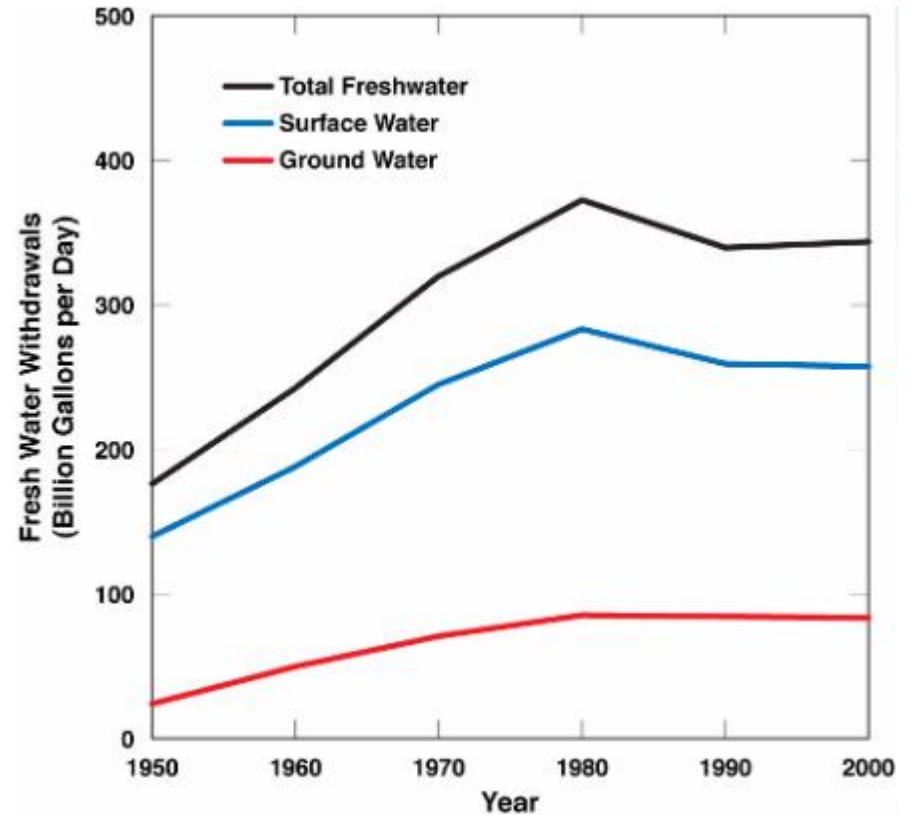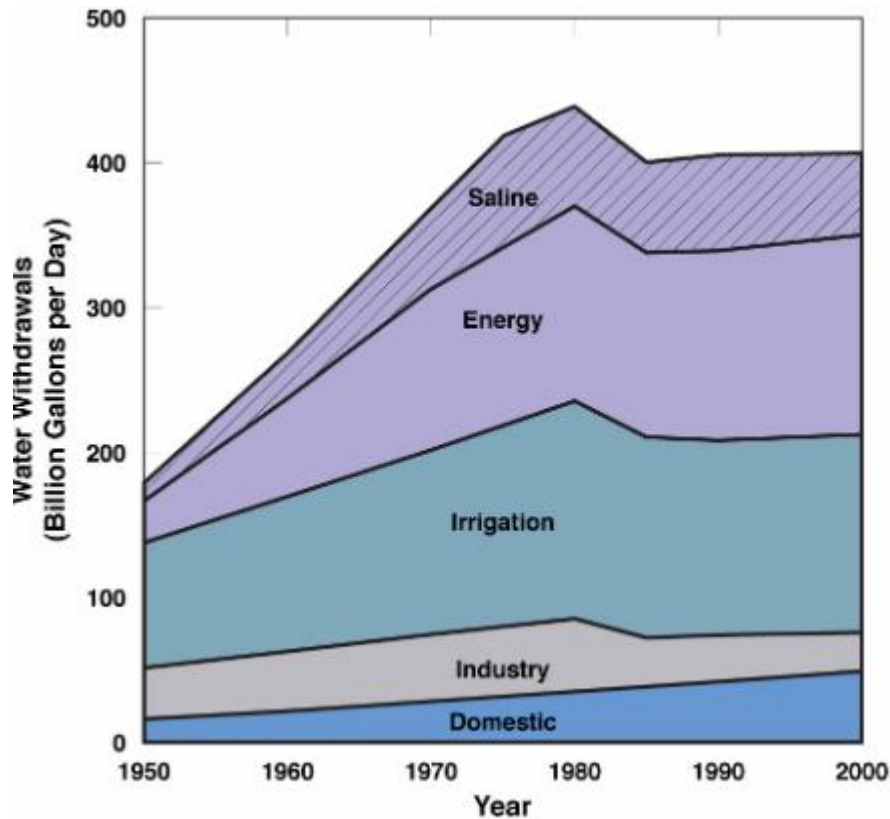
Not an emissions play – water vapor from power plants

But there is an important fundamental difference between emissions of water vapor and emissions of CO_2 and methane. Unlike carbon dioxide and methane, the concentration of water vapor in atmosphere fluctuates rapidly with changes in the temperature and pressure of the air. That is, a molecule of water vapor emitted from a power plant will condense out if and when the air gets cold, and the associated greenhouse gas effect will end. Not so with CO_2 and methane - they stay in the atmosphere and redirect photons until they undergo a chemical reaction. Once emitted, these molecules can remain in the atmosphere for decades or centuries.

The natural water cycle maintains a relatively constant humidity in the global atmosphere and so the effective lifetime of water vapor emissions is a few weeks or less. It is because of this effect, the very short "lifetime" of water vapor emissions in the atmosphere, that water vapor emissions do not exert significant direct greenhouse effects.

**Table 3. Worldwide potential emissions from power production**

Water vapor source	Amount (Billion metric tons)
Combustion-based	1,410
Drying and cooling water	7,014
Total from thermoelectric power (all worldwide fossil fuel resources)	**8,424**

This conservative estimate calculates that conversion of all worldwide fossil fuels for thermoelectric power will generate roughly 1×10^{16} kilograms (kg) of water vapor, Table 3. To put this in perspective, the current amount of water vapor in the atmosphere is 1.3×10^{16} kg water[x]. Spreading the effect of the conversion over 100 years gives a water vapor emissions rate of 1×10^{14} kg water vapor per year. This is roughly 1% of the total amount of water vapor in the atmosphere or 0.02% of annual rainfall worldwide (5×10^{17} kg water).

Name of Plant / Company	Type	Location	Year	Impact	Details
Millstone	Nuclear	Waterford, CT	2012	Cooling	One reactor shut down because water from Long Island Sound was too warm
	Nuclear	Braidwood, IL		Cooling	Needed to obtain special permission to operate with cooling water pond 4 degrees above normal limit
	Oil/gas extraction	KS, TX, PA, ND	2012	Oil/gas production	Denied access to water for at least six weeks
	Hydro	CA	2012	Generation	Reduced snowpack in Sierra Nevada reduced power generation by 38% compared to previous summer
	Oil/gas extraction	Grand Prairie, TX	2011	Generation	Banned use of city water for hydraulic fracturing during certain drought conditions
Bonneville Power Administration	Hydro		2010	Generation	Insufficient hydro generation associated with drought resulted in $164m loss in FY2010
Hoover Dam	Hydro	NV	2010	Generation	Capacity reduced by 23%
NV Energy	Coal		2009	Plant construction	Abandoned a plan for a 1500MW power plant that would have used 1.7m gal water/hr
	Hydro	Chattahoochie River	2007	Generation	Severe drought reduced hydro generation in the Southeast by 45%
North Platte Project	Hydro		2006	Generation	Power production reduced by 50%
	Thermal	TN	2002	Plant construction	Moratorium on installation of new merchant power plants because of cooling constraints
	Thermal	AZ	2002	Plant construction	Arizona rejected permitting for proposed power plant because of impact to local aquifer
Brayton Point	Coal	MA/RI	2004	Cooling	EPA mandated a 94% reduction in water withdrawal, replacing seawater with freshwater cooling towers due to 87% reduction in fin fish

BP study – schematic of cooling types
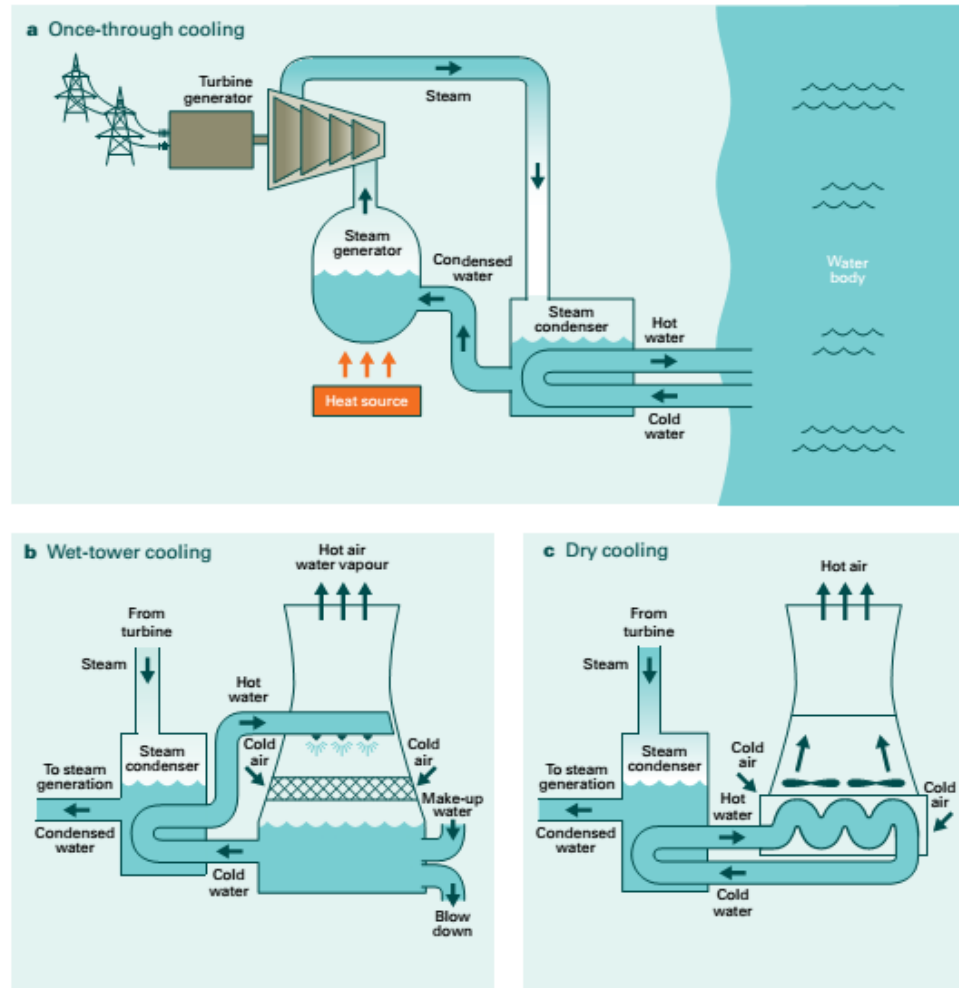
Withdrawals stay steady b/c of efficiency gains, even though the population is growing
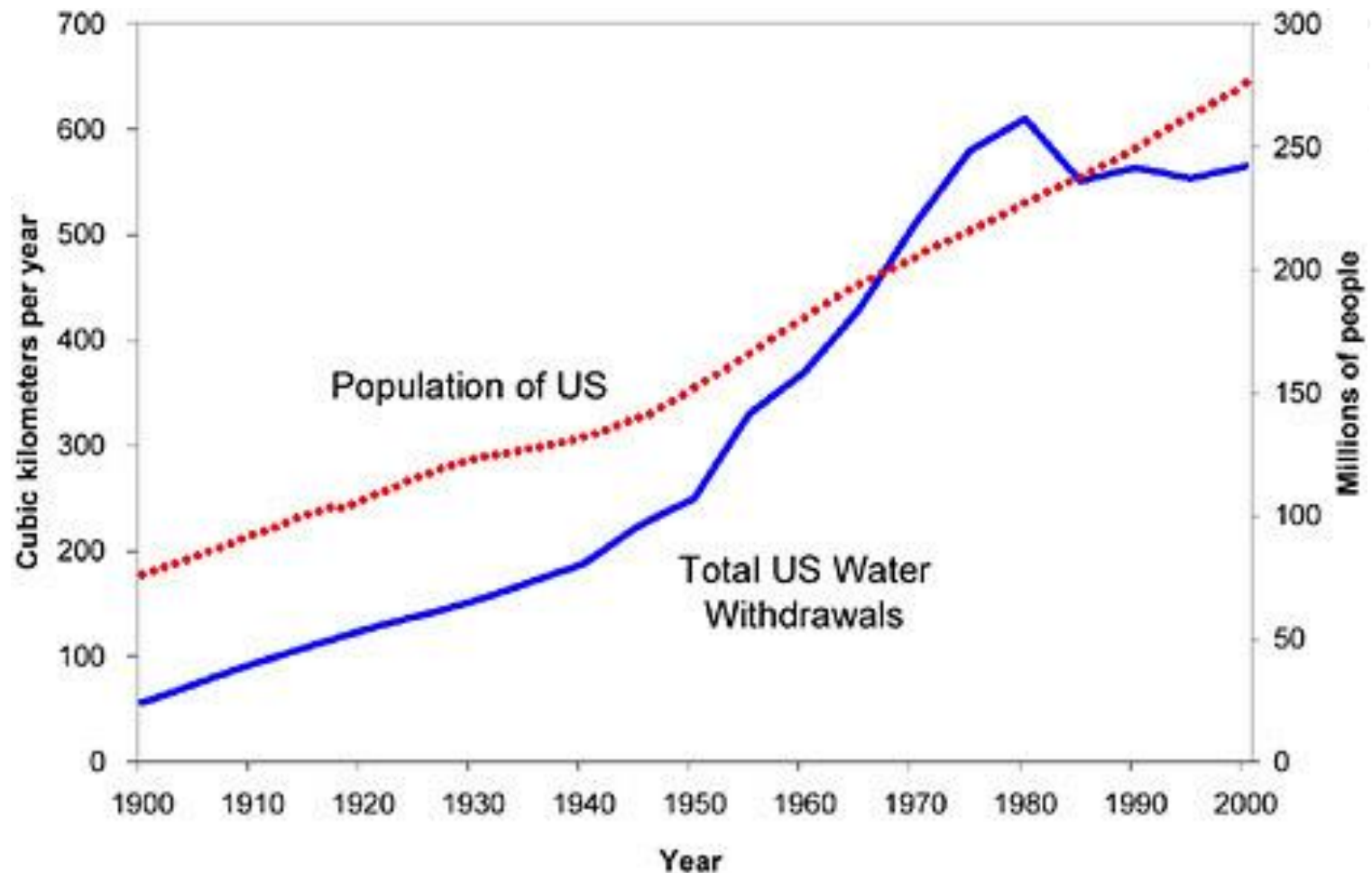
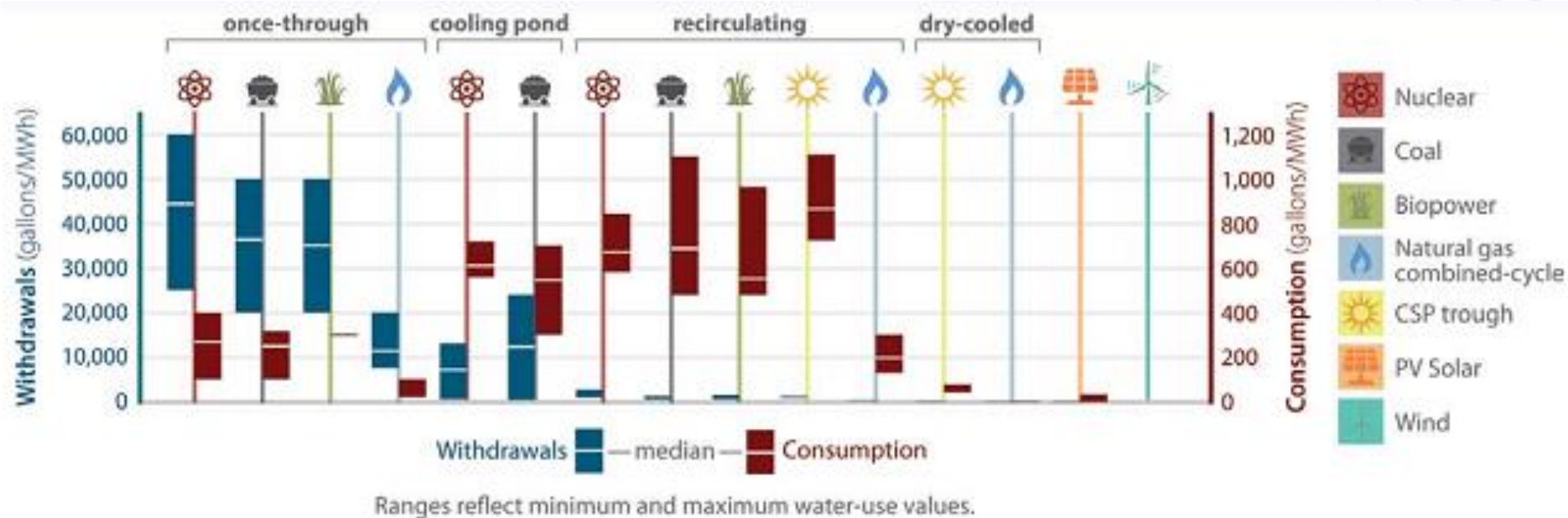# DOE report – water use for energy types

Figure 13. Water use by fuel and cooling technology
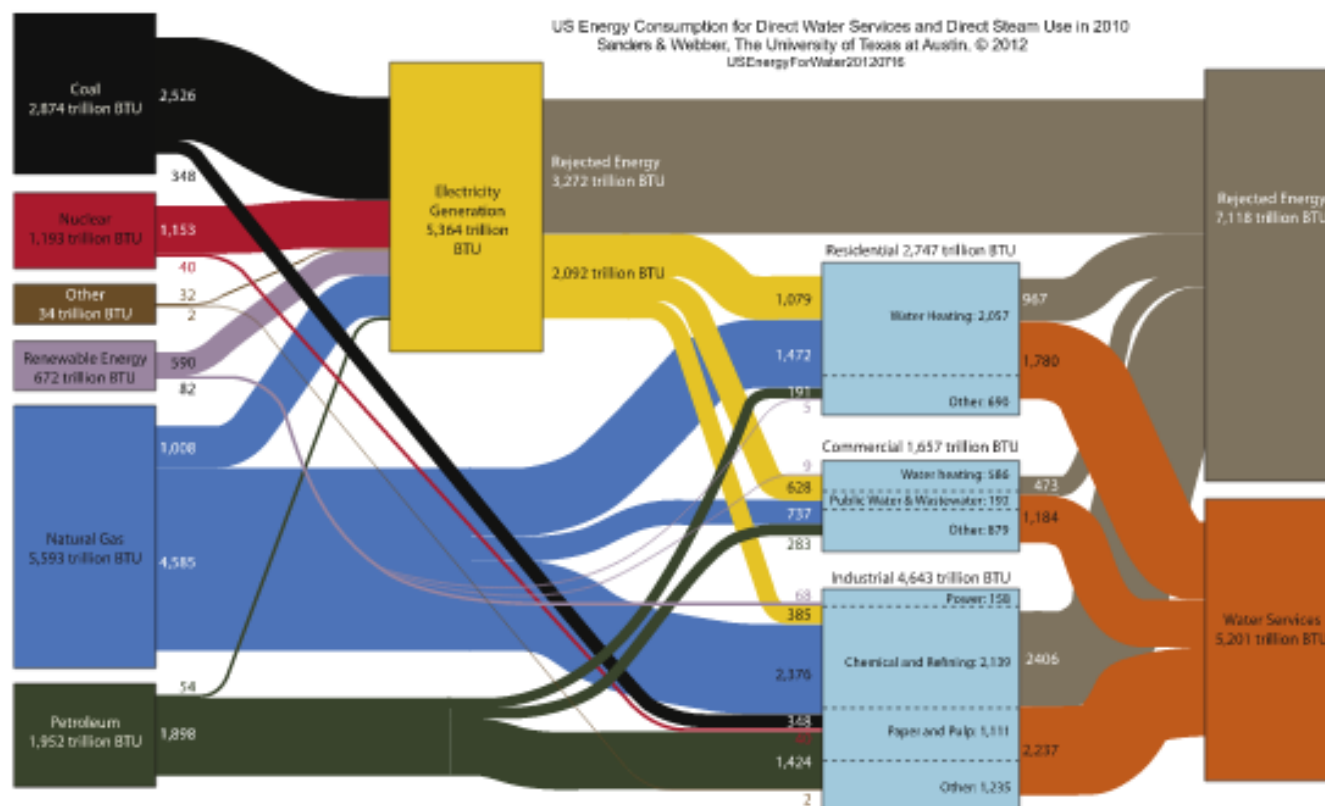
Source: Adapted from Averyt et al. 2011

Figure 3. This diagram summarizes the water-related energy flows in the United States included in the direct water services and direct steam use categories. Primary fuels (on the left) are used directly and indirectly via electricity generation for different purposes (on the right). The thickness of the flows is proportional to the amount of energy consumed. About 58% of the total energy consumption is lost as waste heat. Note: the 5.4 quads used for electricity generation only includes retail electricity sold to residential, commercial and industrial customers; the primary energy consumed for electricity generated and used on-site is included in the sector where it was generated.
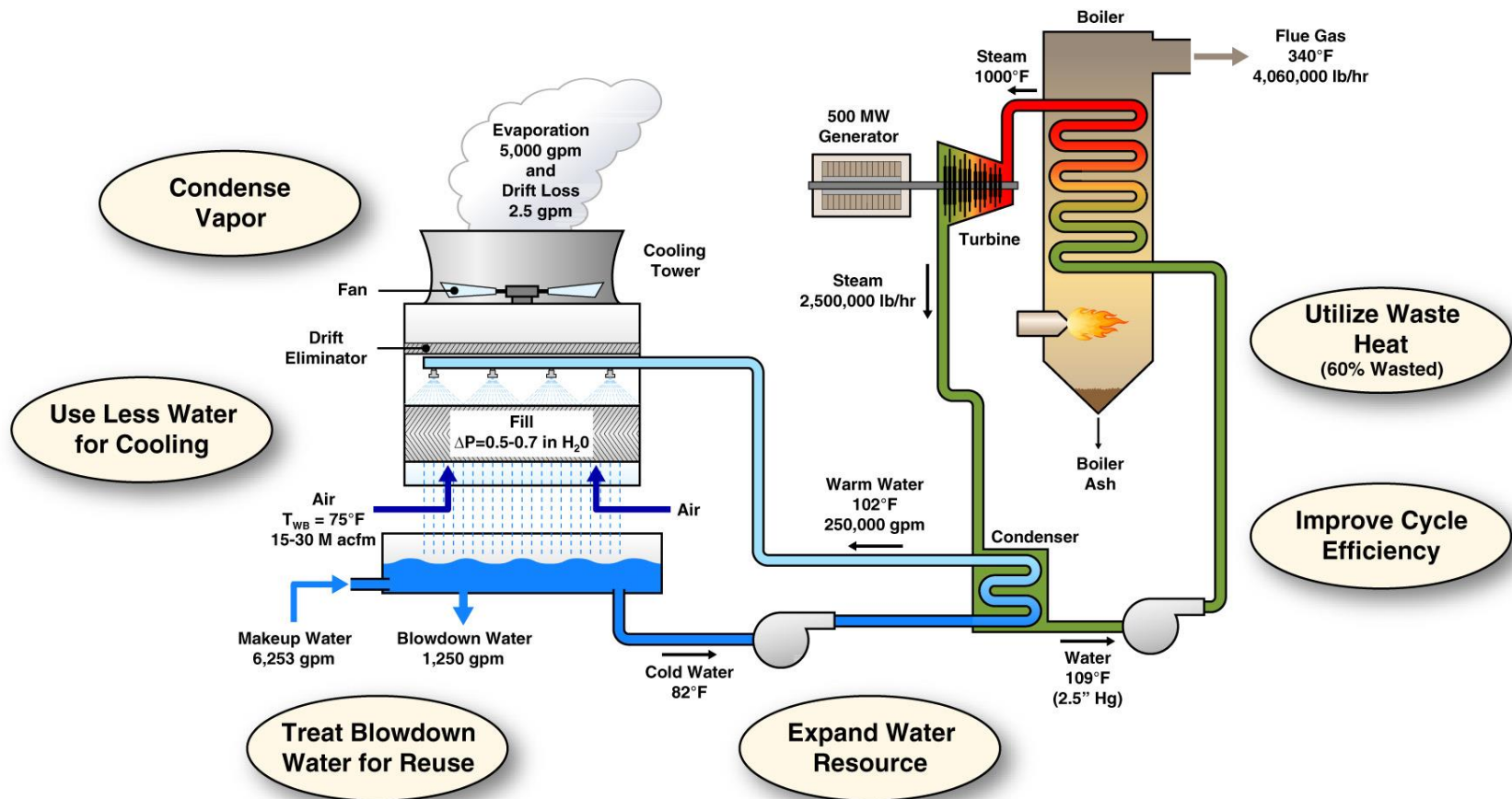
130

CHANGING WHAT'S POSSIBLE

4. Water temp rise making water cooling less attractive/possible

Power plant dependence on water can create a range of problems, including for the plants themselves. Plants have recently run into three kinds of challenges: incoming cooling water that is too warm for efficient and safe operation, cooling water that is too hot for safe release into nearby rivers or lakes, and inadequate water supplies. In response, operators must reduce plant output or discharge hot water anyway, at times when demand for electricity is high and rivers and lakes are already warm

Next steps: Internal analysis to better understand the extent of this issue and its implications.

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Teledyne absorption cooling heat pipe concept

Proposed next steps:

•Fund group through a grant to develop a thermal model and basic cost model to show benefit. Increased efficiency? Reduced area required? Etc.

• Fund team through IDEAS to build a prototype heat pump to demo concept.

There are many opportunities for water reduction in thermoelectric power plants

ARPA-E focus: eliminate the cooling tower via innovative condenser technology

Approaches that are currently being pursued

‣ Use alternative sources of water for cooling (for example, wastewater). Shortcomings…

  – disadvantages to using reclaimed water – one is that you've got to do more cleaning of your equipment, and more cleaning of the water that's discharged

‣ Air cooling

  – 1% of air cooling in US now

  – Where it is internationally

  – Why has it not been used more? performance and cost

  – Compare to wet cooling

  – Talk about dry bulb vs wet bulb temperature

‣ Others?

Folsom Lake - July 20, 2011

Folsom Lake - January 16, 2014

http://www.nasa.gov/sites/default/files/earth20140225-full.jpg

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http://3.bp.blogspot.com/-QXFRbtji88Q/UwZ-bneuM5I/AAAAAAAADXc/qMlzBxcs24I/s1600/la-me-folsom-lake03-jpg-20140115.jpg

Wet bulb vs dry bulb

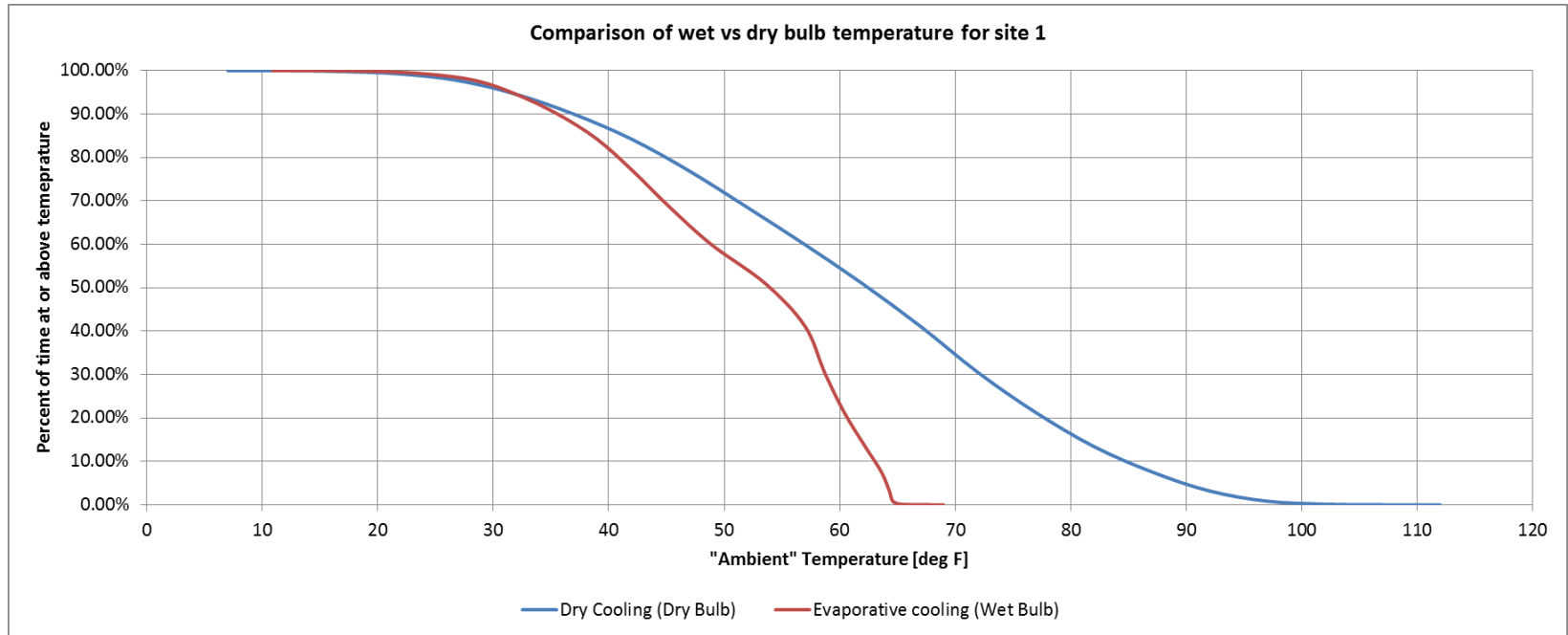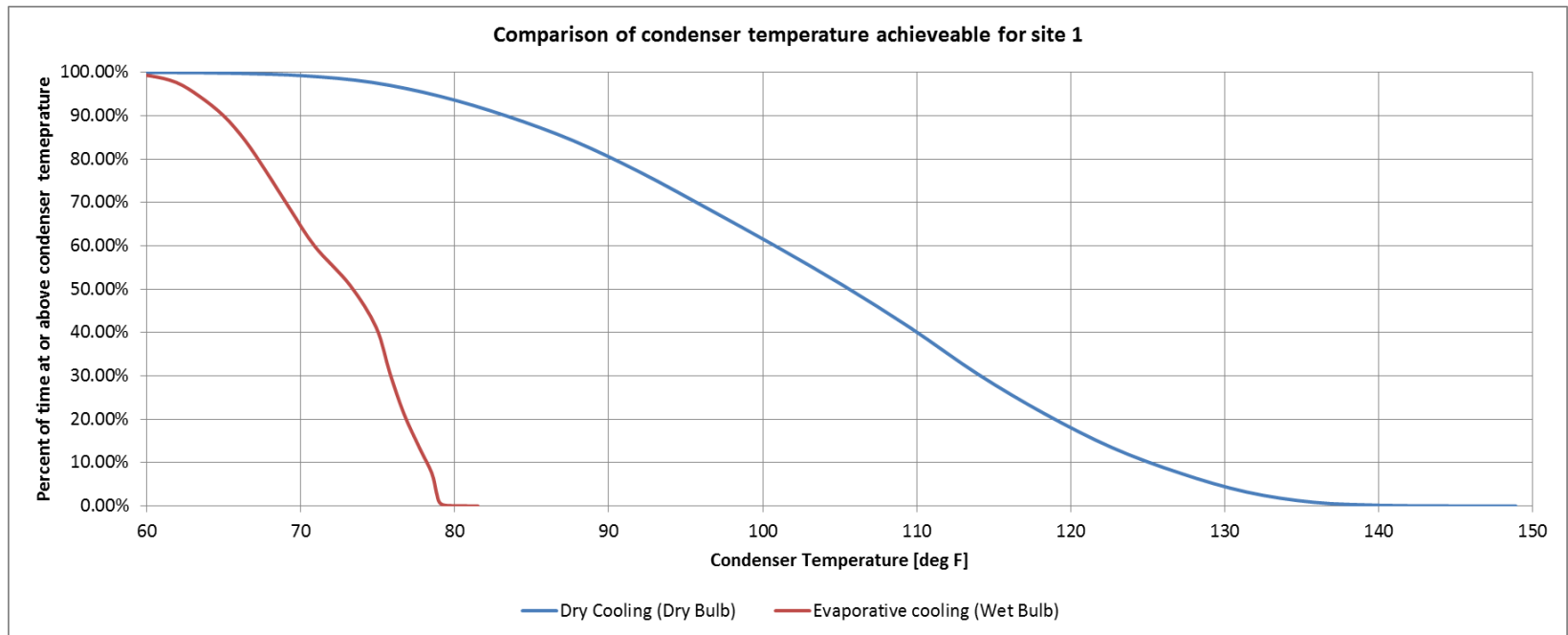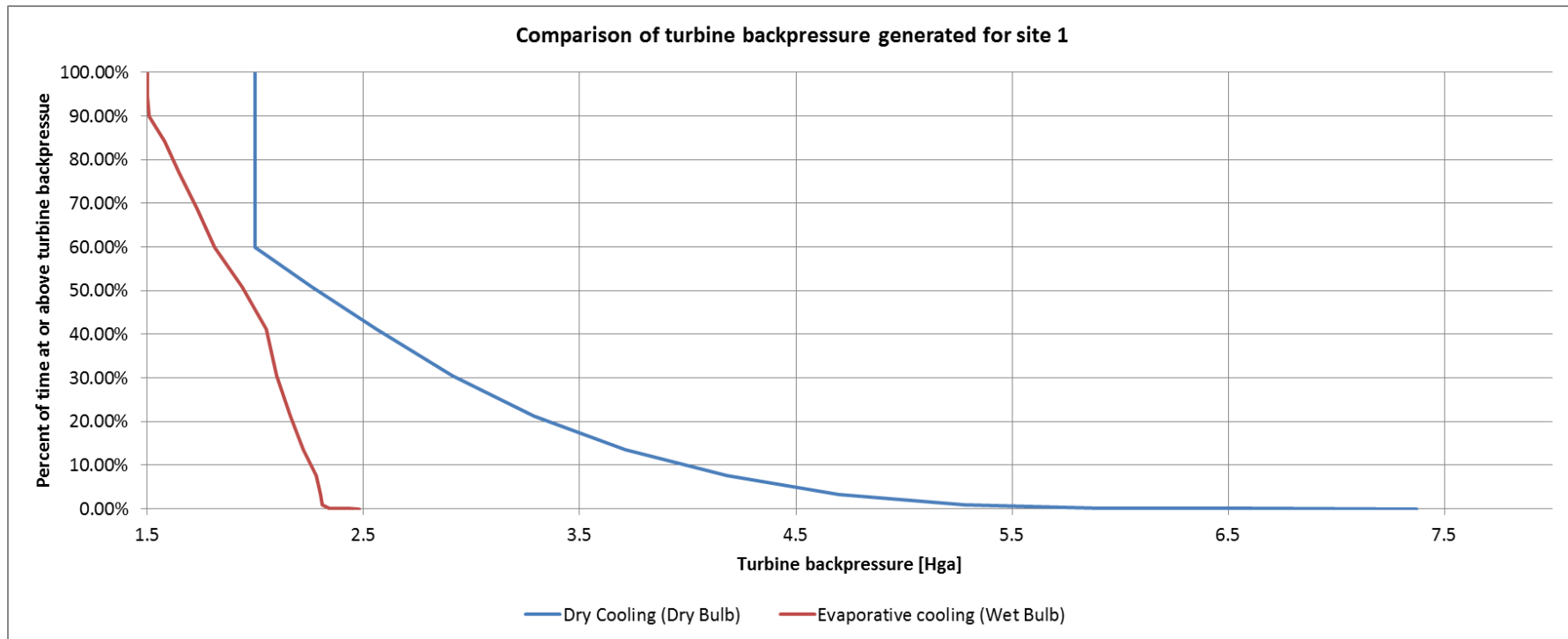**EL PASO   TX**   WMO No. 722700

Dry-Bulb Temperature Hours For An Average Year   (Sheet 5 of 5)

Period of Record = 1972 to 1996

Annual Totals

Temperature Range (°F)	01 To 08	09 To 16	17 To 00	Total Obs	MCWB (°F)
110 / 114		1	0	1	67.8
105 / 109		9	3	12	65.3
100 / 104		43	18	61	64.6
95 / 99	0	145	62	207	64.3
90 / 94	2	255	130	387	63.6
85 / 89	15	304	191	510	62.2
80 / 84	79	333	270	682	60.4
75 / 79	205	293	308	806	58.7
70 / 74	354	267	313	934	57.0
65 / 69	342	242	272	856	53.6
60 / 64	285	252	254	791	48.9
55 / 59	249	245	257	751	45.3
50 / 54	267	209	256	732	42.1
45 / 49	276	147	219	642	39.0
40 / 44	253	89	163	505	35.6
35 / 39	237	49	115	401	32.0
30 / 34	190	26	61	277	28.5
25 / 29	104	8	21	133	24.3
20 / 24	43	2	6	51	20.1
15 / 19	13	1	2	16	15.6
10 / 14	3	0	0	3	10.9
5 / 9	1		0	1	6.6
0 / 4	0			0	3.0

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Comparison of wet vs dry bulb temperature for site 1

Comparison of condenser temperature achieveable for site 1

Comparison of turbine backpressure generated for site 1

EPRI/NSF running a program to improve air cooled systems

- Goals of program:

- But, we argue that this won't get us all the way there – still limited by dry bulb temperature, so still need to cool return water. Otherwise, turbine backpressure.
- EPRI's preliminary first-order estimates show that cooling innovations resulting in a 15°C reduction of the steam-condensing temperature, from 50°C to 35°C, would result in 5% more power production
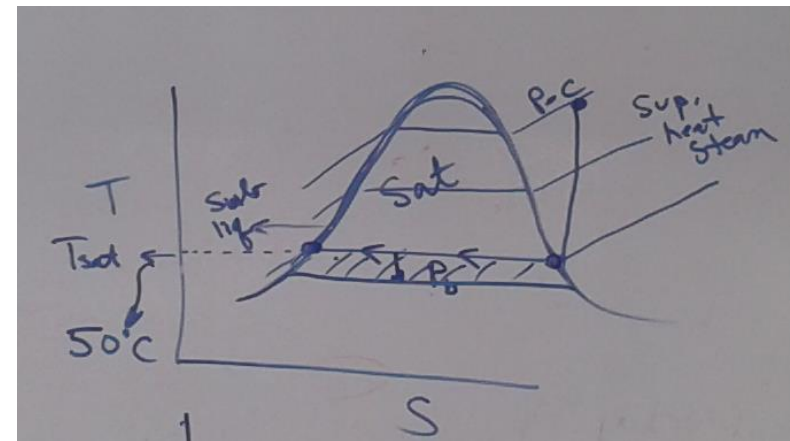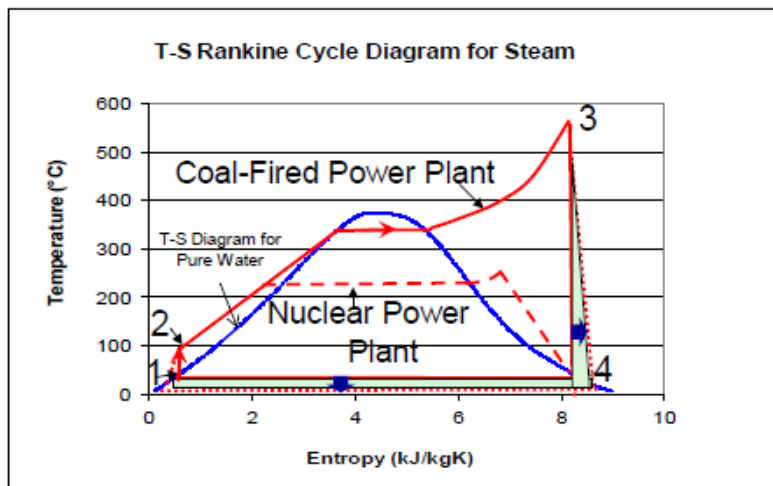
Potential for 5% (1st Order Estimate) more power production or $11M more annual income ($0.05/kWh) for a 500 MW power plant due to reduced steam condensing temperature from 50 °C to 35 °C.
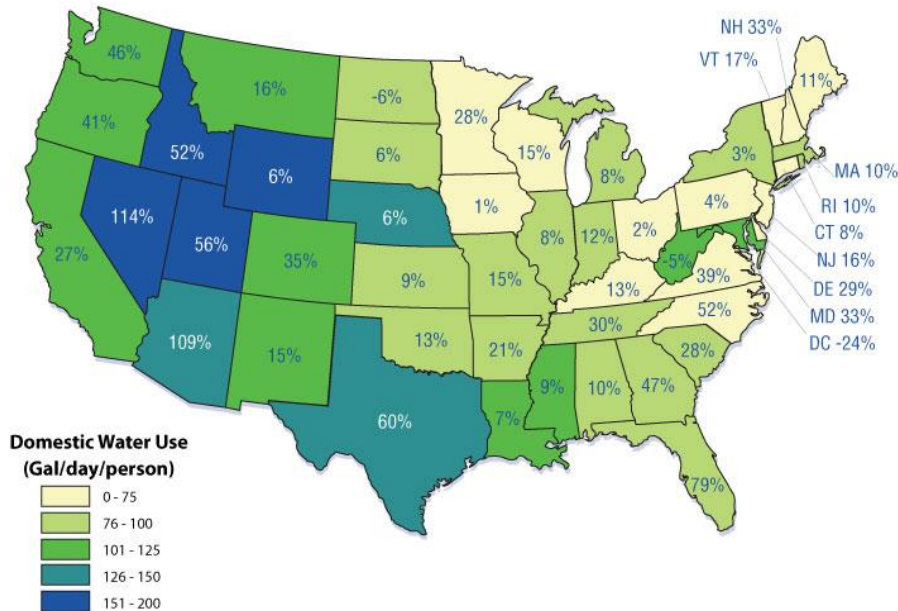
Distribution of Power Plant Intakes by Depth from Surface*
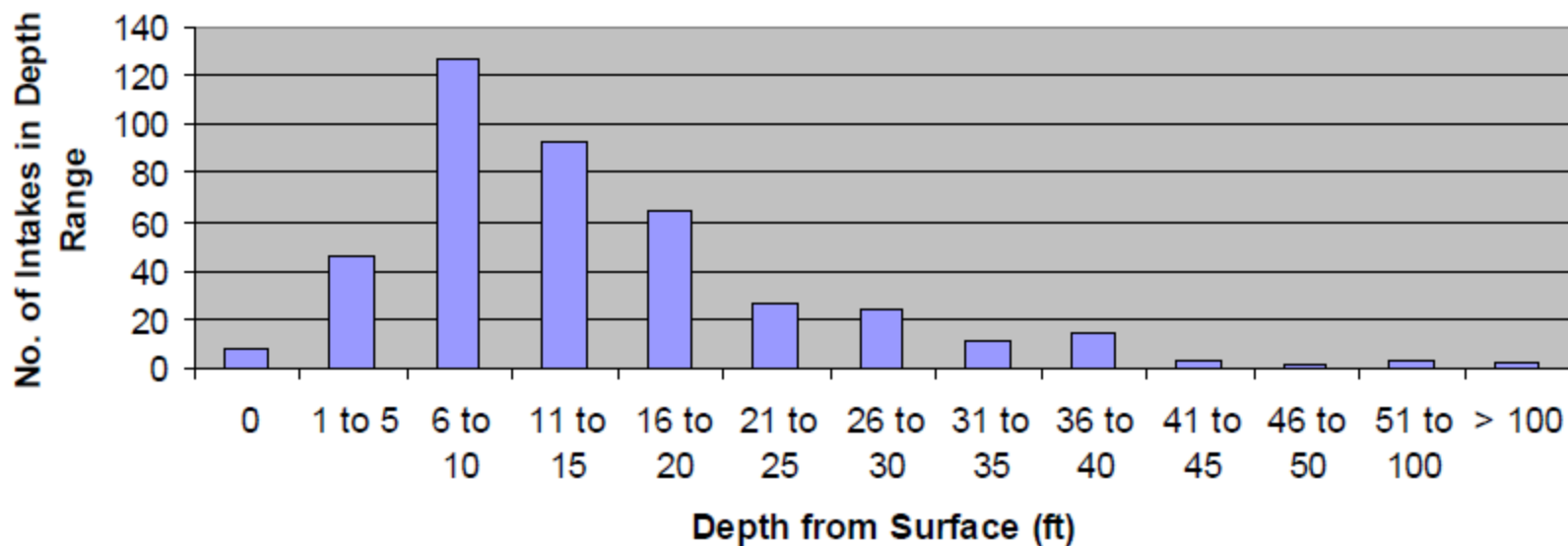
Reason to believe water availability and quality challenges will only get worse

Population growth

Domestic Water Use in Gallons per Day per Person and Projected Percent population Change by 2030

Domestic Water Use in Gallons per Day per Person and Projected Percent Population Change by 2030 (Source: Water data from USGS, Estimated Use of Water in the United States in 2000, County-level data for 2000; population data from U.S. Census Bureau, State Interim Population Projections: 2004–2030)

Climate change
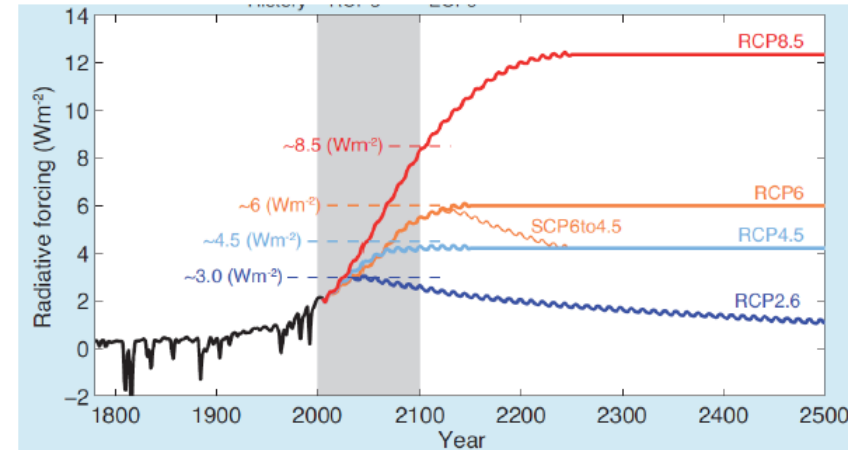
Green house gas emission scenarios of climate models (Source: IPCC AR 5 Working Group I)